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(21) International Application Number: PCT/US00/03805 (22) International Filing Date: 14 February 2000 (14.02.2000) (30) Priority Data: 09/249,955 12 February 1999 (12.02.1999) US (60) Parent Application or Grant BOARD OF REGENTS, THE UNIVERSITY OF TEXAS SYSTEM [/]; (). BECKER, Frederick, F. [/]; (). GASCOYNE, Peter [/]; (). WANG, Xiaobo [/]; (). VYKOUKAL, Jody [/]; (). DE GASPERIS, Giovanni [/]; (). BECKER, Frederick, F. [/]; (). GASCOYNE, Peter [/]; (). WANG, Xiaobo [/]; (). VYKOUKAL, Jody [/]; (). DE GASPERIS, Giovanni [/]; (). HIGHLANDER, Steven, L. ; ().		Published
(54) Title: METHOD AND APPARATUS FOR PROGRAMMABLE FLUIDIC PROCESSING (54) Titre: PROCEDE ET DISPOSITIF POUR TRAITEMENT FLUIDIQUE PROGRAMMABLE (57) Abstract <p>A method and apparatus for microfluidic processing by programmably manipulating a packet. A material is introduced onto a reaction surface and compartmentalized to form a packet. A position of the packet is sensed with a position sensor. A programmable manipulation force is applied to the packet at the position. The programmable manipulation force is adjustable according to packet position by a controller. The packet is programmably moved according to the programmable manipulation force along arbitrarily chosen paths.</p> (57) Abrégé <p>L'invention concerne un procédé et un dispositif pour traitement microfluidique par manipulation programmable de paquet. On introduit un matériau sur une surface de réaction en procédant à une mise en paquet compartimentée. La position d'un paquet est déterminée via un capteur de position. Une force de manipulation programmable est appliquée au paquet, dans la position correspondante. Ladite force est réglable en fonction de la position du paquet, via une unité de commande. Le paquet est déplacé en mode programmable, selon la force considérée, le long de trajets choisis arbitrairement.</p>		

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(21) International Application Number: PCT/US00/03805 (22) International Filing Date: 14 February 2000 (14.02.00) (30) Priority Data: 09/249,955 12 February 1999 (12.02.99) US (63) Related by Continuation (CON) or Continuation-in-Part (CIP) to Earlier Application US 09/249,955 (CON) Filed on 12 February 1999 (12.02.99) (71) Applicant (for all designated States except US): BOARD OF REGENTS, THE UNIVERSITY OF TEXAS SYSTEM [US/US]; 201 W. Seventh Street, Austin, TX 78701 (US). (72) Inventors; and (75) Inventors/Applicants (for US only): BECKER, Frederick, F. [US/US]; 8 Hunter's Branch, Houston, TX 77024 (US). GASCOYNE, Peter [US/US]; 5313 Huisache Street, Bellaire, TX 77401 (US). WANG, Xiaobo [CN/US]; 4910 Winding River Drive, Sugarland, TX 77478 (US). VYKOUKAL, Jody [US/US]; 1937 Dryden No. 2, Houston, TX 77030 (US). DE GASPERIS, Giovanni [IT/US]; Via Giovanni Feneziani 14, I-67100 L'Aquila (IT).		(74) Agent: HIGHLANDER, Steven, L.; Fulbright & Jaworski, 2400 One American Center, 600 Congress Avenue, Austin, TX 78701 (US). (81) Designated States: CA, JP, US, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE). Published <i>Without international search report and to be republished upon receipt of that report.</i>
(54) Title: METHOD AND APPARATUS FOR PROGRAMMABLE FLUIDIC PROCESSING (57) Abstract A method and apparatus for microfluidic processing by programmably manipulating a packet. A material is introduced onto a reaction surface and compartmentalized to form a packet. A position of the packet is sensed with a position sensor. A programmable manipulation force is applied to the packet at the position. The programmable manipulation force is adjustable according to packet position by a controller. The packet is programmably moved according to the programmable manipulation force along arbitrarily chosen paths.		

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Description

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METHOD AND APPARATUS FOR PROGRAMMABLE FLUIDIC PROCESSING

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to fluidic processing and, more particularly, to a method and apparatus for programmably manipulating and interacting one or more compartmentalized packets of material on a reaction surface.

2. Description of Related Art

Chemical protocols often involve a number of processing steps including metering, mixing, transporting, division, and other manipulation of fluids. For example, fluids are often prepared in test tubes, metered out using pipettes, transported into different test tubes, and mixed with other fluids to promote one or more reactions. During such procedures, reagents, intermediates, and/or final reaction products may be monitored, measured, or sensed in analytical apparatus. Microfluidic processing generally involves such processing and monitoring using minute quantities of fluid. Microfluidic processing finds applications in vast fields of study and industry including, for instance, diagnostic medicine, environmental testing, agriculture, chemical and biological warfare detection, space medicine, molecular biology, chemistry, biochemistry, food science, clinical studies, and pharmaceutical pursuits.

A current approach to fluidic and microfluidic processing utilizes a number of microfluidic channels that are configured with microvalves, pumps, connectors, mixers, and detectors. While devices using micro-scale implementations of these traditional approaches may exhibit at least a degree of utility, vast room for improvement remains. For instance, pumps and valves used in traditional fluidic transportation are mechanical. Mechanical devices, particularly when coupled to thin microchannels, may be prone to failure or blockage. In particular, thin channels may become narrowed or partially-blocked due to buildup of channel contamination, which, in turn, may lead to mechanical failure of associated devices. Current microfluidic devices also lack flexibility, for they rely upon a fixed pathway of microchannels. With fixed pathways, devices are limited in

1 the number and type of tasks they may perform. Also, using fixed pathways makes many
2 types of metering, transport, and manipulation difficult. With traditional devices, it is
3 difficult to partition one type of sample from another within a channel.

4 Electrical properties of materials have been employed to perform a limited
5 number of fluidic processing tasks. For example, dielectrophoresis has been utilized to
6 aid in the characterization and separation of particles, including biological cells. An
7 example of such a device is described in U. S. Patent No. 5,344,535 to Betts, incorporated
8 herein by reference. Betts establishes dielectrophoretic collection rates and collection rate
9 spectra for dielectrically polarizable particles in a suspension. Particle concentrations at a
10 certain location downstream of an electrode structure are measured using a light source
11 and a light detector, which measures the increased or decreased absorption or scattering
12 of the light which, in turn, indicates an increase or decrease in the concentration of
13 particles suspended in the fluid. Although useful for determining particle
14 dielectrophoretic properties, such a system is limited in application. In particular, such a
15 system does not allow for general fluidic processing involving various interactions,
16 sometimes performed simultaneously, such as metering, mixing, fusing, transporting,
17 division, and general manipulation of multiple reagents and reaction products.

18 Another example of using certain electrical properties for specific types of
19 processing is disclosed in U.S. Patent No. 5,632,957 to Heller *et al.*, incorporated herein
20 by reference. There, controlled hybridization may be achieved using a matrix or array of
21 electronically addressable microlocations in conjunction with a permeation layer, an
22 attachment region and a reservoir. An activated microlocation attracts charged binding
23 entities towards an electrode. When the binding entity contacts the attachment layer,
24 which is situated upon the permeation layer, the functionalized specific binding entity
25 becomes covalently attached to the attachment layer. Although useful for specific tasks
26 such as DNA hybridization, room for improvement remains. In particular, such a system,
27 utilizing attachment sites for certain binding entities is designed for particular
28 applications and not for general fluidic processing of a variety of fluids. More

1 specifically, such a system is designed for use with charged binding entities that interact
2 with attachment sites.

3 Another example of processing is disclosed in U.S. Patent No. 5,126,022 to Soane
4 *et al.*, incorporated herein by reference. There, charged molecules may be moved through
5 a medium that fills a trench in response to electric fields generated by electrodes.
6 Although useful for tasks such as separation, room for improvement remains in that such
7 devices are not well suited for performing a wide variety of fluidic processing interactions
8 on a wide variety of different materials.

9 There are other examples of using dielectrophoresis for performing specific,
10 limited fluidic processing tasks. U.S. Patent No. 5,795,457 to Pethig and Burt,
11 incorporated herein by reference, disclose a method for promoting reactions between
12 particles suspended in liquid by applying two or more electrical fields of different
13 frequencies to electrode arrays. While perhaps useful for facilitating certain interactions
14 between many particles of different types, the method is not well suited for general fluidic
15 processing. U.S. Patent No. 4,390,403 to Batchelder, incorporated herein by reference,
16 discloses a method and apparatus for manipulation of chemical species by
17 dielectrophoretic forces. Although useful for inducing certain chemical reactions, its
18 flexibility is limited, and it does not allow for general, programmable fluidic processing.

19 Any problems or shortcomings enumerated in the foregoing are not intended to be
20 exhaustive but rather are among many that tend to impair the effectiveness of previously
21 known processing techniques. Other noteworthy problems may also exist; however,
22 those presented above should be sufficient to demonstrate that apparatus and methods
23 appearing in the art have not been altogether satisfactory.

24 SUMMARY OF THE INVENTION

25 In one respect, the invention is an apparatus for programmably manipulating a
26 packet. As used herein, "packet" refers to compartmentalized matter and may refer to a
27 fluid packet, an encapsulated packet, and/or a solid packet. A fluid packet refers to one or
28 more packets of liquids or gases. A fluid packet may refer to a droplet or bubble of a

1 liquid or gas. A fluid packet may refer to a droplet of water, a droplet of reagent, a
2 droplet of solvent, a droplet of solution, a droplet of sample, a particle or cell suspension,
3 a droplet of an intermediate product, a droplet of a final reaction product, or a droplet of
4 any material. An example of a fluid packet is a droplet of aqueous solution suspended in
5 oil. An encapsulated packet refers to a packet enclosed by a layer of material. An
6 encapsulated packet may refer to vesicle or other microcapsule of liquid or gas that may
7 contain a reagent, a sample, a particle, a cell, an intermediate product, a final reaction
8 product, or any material. The surface of an encapsulated packet may be coated with a
9 reagent, a sample, a particle or cell, an intermediate product, a final reaction product, or
10 any material. An example of an encapsulated packet is a lipid vesicle containing an
11 aqueous solution of reagent suspended in water. A solid packet refers to a solid material
12 that may contain, or be covered with a reagent, a sample, a particle or cell, an
13 intermediate product, a final reaction product, or any material. An example of a solid
14 packet is a latex microsphere with reagent bound to its surface suspended in an aqueous
15 solution. Methods for producing packets as defined herein are known in the art. Packets
16 may be made to vary greatly in size and shape, but in embodiments described herein,
17 packets may have a diameter between about 100 nm and about 1 cm.

18 In this respect, the invention includes a reaction surface, an inlet port, means for
19 generating a programmable manipulation force upon the packet, a position sensor, and a
20 controller. The reaction surface is configured to provide an interaction site for the packet.
21 The inlet port is coupled to the reaction surface and is configured to introduce the packet
22 onto the reaction surface. The means for generating a programmable manipulation force
23 upon the packet programmably moves the packet about the reaction surface along
24 arbitrarily chosen paths. As used herein, by "arbitrarily chosen paths" it is meant that
25 paths may be chosen to have any shape about the reaction surface. Arbitrarily chosen
26 paths are not limited to movements that are predefined. Arbitrarily chosen paths may be
27 modified in an unlimited manner about the reaction surface and may hence trace out any
28 pattern. The position sensor is coupled to the reaction surface and is configured to sense
29 a position of the packet on the reaction surface. The controller is coupled to the means
30 for generating a programmable manipulation force and to the position sensor. The

1 controller is configured to adjust the programmable manipulation force according to the
2 position.

3 In other aspects, the apparatus may also include an outlet port coupled to the
4 reaction surface. The outlet port may be configured to collect the packet from the
5 reaction surface. The means for generating a manipulation force may include a conductor
6 adapted to generate an electric field. The means for generating a manipulation force may
7 include a light source. The manipulation force may include a dielectrophoretic force, an
8 electrophoretic force, an optical force, a mechanical force, or any combination thereof.
9 The position sensor may include a conductor configured to measure an electrical
10 impedance of the packet. The position sensor may include an optical system configured
11 to monitor the position of the packet. The means for generating a programmable
12 manipulation force and the position sensor may be integral.

13 In another respect, the invention is an apparatus for microfluidic processing by
14 programmably manipulating packets. The apparatus includes a reaction surface, an inlet
15 port, an array of driving electrodes, and an array of impedance sensing electrodes. As
16 used herein, an "array" refers to any grouping or arrangement. An array may be a linear
17 arrangement of elements. It may also be a two dimensional grouping having columns and
18 rows. Columns and rows need not be uniformly spaced or orthogonal. An array may also
19 be any three dimensional arrangement. The reaction surface is configured to provide an
20 interaction site for the packets. The inlet port is coupled to the reaction surface and is
21 configured to introduce the packets onto the reaction surface. The array of driving
22 electrodes is coupled to the reaction surface and is configured to generate a
23 programmable manipulation force upon the packets to direct the microfluidic processing
24 by moving the packets along arbitrarily chosen paths. The array of impedance sensing
25 electrodes is coupled to the reaction surface and is configured to sense positions of the
26 packets during the microfluidic processing.

27 In other aspects, the apparatus may also include an outlet port coupled to the
28 reaction surface. The outlet port may be configured to collect the packets from the
29 reaction surface. The apparatus may also include a controller coupled to the array of

1 driving electrodes and to the array of impedance sensing electrodes. The controller may
2 be adapted to provide a feedback from the array of impedance sensing electrodes to the
3 array of driving electrodes. The array of driving electrodes and the array of impedance
4 sensing electrodes may be integral. The apparatus may also include an integrated circuit
5 coupled to the array of driving electrodes and to the array of impedance sensing
6 electrodes. The apparatus may also include a coating modifying a hydrophobicity of the
7 reaction surface. The apparatus may also include a maintenance port.

8 In another respect, the invention is an apparatus for processing packets in a
9 partitioning medium. As used herein, a "partitioning medium" refers to matter that may
10 be adapted to suspend and compartmentalize other matter to form packets on a reaction
11 surface. A partitioning medium may act by utilizing differences in hydrophobicity
12 between a fluid and a packet. For instance, hydrocarbon molecules may serve as a
13 partitioning medium for packets of aqueous solution because molecules of an aqueous
14 solution introduced into a suspending hydrocarbon fluid will strongly tend to stay
15 associated with one another. This phenomenon is referred to as a hydrophobic effect, and
16 it allows for compartmentalization and easy transport of packets upon or over a surface.
17 A partitioning medium may also be a dielectric carrier liquid which is immiscible with
18 sample solutions. Other suitable partitioning mediums include, but are not limited to, air,
19 aqueous solutions, organic solvents, oils, and hydrocarbons. The apparatus includes a
20 chamber, a programmable dielectrophoretic array, and an impedance sensing array. As
21 used herein, a "programmable dielectrophoretic array" (PDA) refers to an electrode array
22 whose individual elements can be addressed with different electrical signals. The
23 addressing of electrode elements with electrical signals may initiate different field
24 distributions and generate dielectrophoretic manipulation forces that trap, repel, transport,
25 or perform other manipulations upon packets on and above the electrode plane. By
26 programmably addressing electrode elements within the array with electrical signals,
27 electric field distributions and manipulation forces acting upon packets may be
28 programmable so that packets may be manipulated along arbitrarily chosen or
29 predetermined paths. The chamber is configured to contain the packets and the
30 partitioning medium. The programmable dielectrophoretic array is coupled to the

1 chamber and is configured to generate a programmable dielectrophoretic force to direct
2 processing of the packets. The impedance sensing array of electrodes is integral with the
3 programmable dielectrophoretic array. The impedance sensing array of electrodes is
4 configured to sense a position of the packets within the chamber.

5 In other aspects, the apparatus may also include an integrated circuit coupled to
6 the programmable dielectrophoretic array and to the impedance sensing array of
7 electrodes. The apparatus may also include a controller coupled to the programmable
8 dielectrophoretic array and to the impedance sensing array of electrodes. The controller
9 may be adapted to provide a feedback from the impedance sensing array of electrodes to
10 the programmable dielectrophoretic array. The electrodes may be between about 1
11 micron and about 200 microns and may be spaced between about 1 micron and about 200
12 microns.

13 In another respect, the invention is a method for manipulating a packet in which
14 the following are provided: a reaction surface, an inlet port coupled to the reaction
15 surface, means for generating a programmable manipulation force upon the packet, a
16 position sensor coupled to the reaction surface, and a controller coupled to the means for
17 generating a programmable manipulation force and to the position sensor. A material is
18 introduced onto the reaction surface with the inlet port. The material is
19 compartmentalized to form the packet. A position of the packet is sensed with the
20 position sensor. A programmable manipulation force is applied on the packet at the
21 position with the means for generating a programmable manipulation force. The
22 programmable manipulation force is adjustable according to the position by the
23 controller. The packet is programmably moved according to the programmable
24 manipulation force along arbitrarily chosen paths.

25 In other aspects, the packet may include a fluid packet, an encapsulated packet, or
26 a solid packet. The compartmentalizing may include suspending the material in a
27 partitioning medium. The material may be immiscible in the partitioning medium. The
28 reaction surface may include a coating, and the hydrophobicity of the coating may be
29 greater than a hydrophobicity of the partitioning medium. The application of the

1 programmable manipulation force may include applying a driving signal to one or more
2 driving electrodes arranged in an array to generate the programmable manipulation force.
3 The programmable manipulation force may include a dielectrophoretic force, an
4 electrophoretic force, an optical force, a mechanical force, or any combination thereof.
5 The sensing of a position may include applying a sensing signal to one or more
6 impedance sensing electrodes arranged in an array to detect an impedance associated with
7 the packet.

8 In another respect, the invention is a method of fluidic processing in which the
9 following are provided: a reaction surface, an inlet port coupled to the reaction surface, an
10 array of driving electrodes coupled to the reaction surface, and an array of impedance
11 sensing electrodes coupled to the reaction surface. One or more materials are introduced
12 onto the reaction surface with the inlet port. The one or more materials are
13 compartmentalized to form a plurality of packets. A sensing signal is applied to one or
14 more of the impedance sensing electrodes to determine a position of one or more of the
15 plurality of packets. A driving signal is applied to one or more of the driving electrodes
16 to generate a programmable manipulation force on one or more of the plurality of packets
17 at the position. One or more of the plurality of packets are interacted according to the
18 programmable manipulation force.

19 In other aspects, at least one of the plurality of packets may include a fluid packet,
20 an encapsulated packet, or a solid packet. The sensing signal and the driving signal may
21 be a single processing signal. The processing signal may include a first frequency
22 component corresponding to the sensing signal and a second frequency component
23 corresponding to the driving signal. A packet distribution map may be formed according
24 to the positions of the plurality of packets. A position of one or more obstructions on the
25 reaction surface may be determined. The interacting of one or more packets may include
26 moving, fusing, merging, mixing, reacting, metering, dividing, splitting, sensing,
27 collecting, or any combination thereof.

28 In another respect, the invention is a method for manipulating one or more packets
29 on a reaction surface in which the following are provided: a programmable

5 1 dielectrophoretic array coupled to the reaction surface and an impedance sensing array of
2 2 electrodes integral with the programmable dielectrophoretic array. A material is
3 3 introduced onto the reaction surface. The material is compartmentalized to form the one
4 4 or more packets. A path is specified upon the reaction surface. A programmable
10 5 manipulation force is applied with the programmable dielectrophoretic array on the one or
6 6 more packets to move the one or more packets along the path. A position of the one or
7 7 more packets is sensed with the impedance sensing array of electrodes. Whether the
15 8 position corresponds to the path is monitored. The one or more packets are interacted.

9 9 In other aspects, at least one of the one or more packets may include a fluid
10 10 packet, an encapsulated packet, or a solid packet. The method may also include sensing a
20 11 position of an obstruction; determining a modified path, the modified path avoiding the
12 12 obstruction; and applying a programmable manipulation force on the one or more packets
13 13 to move the one or more packets along the modified path. The specification of a path
25 14 may include specifying an initial position and a final position. The introduction of the
15 15 material may include extracting the material with a dielectrophoretic extraction force
16 16 from an injector onto the reaction surface. The interacting of one or more packets may
17 17 include moving, fusing, merging, mixing, reacting, metering, dividing, splitting, sensing,
30 18 collecting, or any combination thereof.

19 19 Other features and advantages of the present invention will become apparent with
20 20 reference to the following description of typical embodiments in connection with the
35 21 accompanying drawings wherein like reference numerals have been applied to like
22 22 elements, in which:

40 24 BRIEF DESCRIPTION OF THE DRAWINGS

25 25 FIG. 1 is a simplified schematic diagram that illustrates a microfluidic device
45 26 according to one embodiment of the presently disclosed method and apparatus.

27 27 FIG. 2 is a simplified illustration of dielectrophoretic force phenomenon.

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5 1 **FIG. 3** illustrates a position sensing system according to one embodiment of the
2 presently disclosed method and apparatus.

3 **FIG. 4** is a three dimensional view of a microfluidic device according to one
10 4 embodiment of the presently disclosed method and apparatus.

5 **FIG. 5** is a side cross sectional view of a microfluidic device according to one
6 embodiment of the presently disclosed method and apparatus.

15 7 **FIG. 6** is a simplified block representation of a microfluidic system according to
8 one embodiment of the presently disclosed method and apparatus.

20 9 **FIG. 7** is a simplified block representation of a signal application arrangement
10 according to one embodiment of the presently disclosed method and apparatus.

11 **FIG. 8** is a cross sectional view of microfluidic device according to one
25 12 embodiment of the presently disclosed method and apparatus.

13 **FIG. 9** is a top view of a microfluidic device according to one embodiment of the
14 presently disclosed method and apparatus.

30 15 **FIG. 9B** is another top view of a microfluidic device according to one
16 embodiment of the presently disclosed method and apparatus.

17 **FIG. 10** is a simplified block representation of a microfluidic system according to
35 18 one embodiment of the presently disclosed method and apparatus.

19 **FIG. 11** is a top view of a microfluidic device showing a microfluidic process
40 20 according to one embodiment of the presently disclosed method and apparatus.

21 **FIG. 12** illustrates certain packet interactions according to one embodiment of the
22 presently disclosed method and apparatus.

45 23 **FIG. 13** is a flow chart showing a microfluidic process according to one
24 embodiment of the presently disclosed method and apparatus..

DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

The disclosed method and apparatus provide many advantages. For instance, they permit the fluidic processing of minute quantities of samples and reagents. The apparatus need not use conventional hardware components such as valves, mixers, pump. The apparatus may be readily miniaturized and its processes may be automated or programmed. The apparatus may be used for many different types of microfluidic processing and protocols, and it may be operated in parallel mode whereby multiple fluidic processing tasks and reactions are performed simultaneously within a single chamber. Because it need not rely on narrow tubes or channels, blockages may be minimized or eliminated. Further, if obstructions do exist, those obstructions may be located and avoided with position sensing techniques.

Allowing for flexible microfluidic processing, the disclosed method and apparatus has vast applications including, but not limited to, blood and urine assays, pathogen detection, pollution monitoring, water monitoring, fertilizer analysis, the detection of chemical and biological warfare agents, food pathogen detection, quality control and blending, massively parallel molecular biological protocols, genetic engineering, oncogene detection, and pharmaceutical development and testing.

In one embodiment of the disclosed method and apparatus, a fluidic device 10 as shown in FIG. 1 is employed. As illustrated, fluidic device 10 may include a reaction surface 12, a port 15, packets 21, wall 22, position sensor 23, a force generator 25, and a controller 81.

In operation, one or more materials may be introduced onto reaction surface 12 through port 15. The one or more materials may be compartmentalized to form packets 21 within a partitioning medium (not shown). Force generator 25 generates a manipulation force on packets 21 to facilitate fluidic manipulations and interactions. In the illustrated embodiment, force generator 25 generates two forces, F_1 and F_2 , that

5 1 manipulate packets 21 and moves them according to the dashed lines of FIG. 1. Position
2 2 sensor 23 senses the positions of packets 21 and is able to monitor any packet
3 3 interactions. As position sensor 23 is coupled to force generator 25 by controller 81, a
4 4 feedback relationship may be established. Such feedback may include determination of
10 5 the position of packets 21 on reaction surface 12 that allows for the application of
6 6 manipulation forces on packets 21 based on position information. The position of
7 7 packets during manipulation may thus be continuously monitored and this information
15 8 may be used to continuously adjust one or more manipulation forces so to achieve
9 9 movement of packets 21 along a desired trajectory to a desired location on reaction
10 10 surface 12.

20 11 In the illustrated embodiment of FIG. 1, forces F_1 or F_2 may include many
12 12 different types of forces. For instance, forces F_1 and F_2 may be dielectrophoretic,
13 13 electrophoretic, optical (as may arise, for example, through the use of optical tweezers),
14 14 mechanical (as may arise, for example, from elastic traveling waves or from acoustic
25 15 waves), or any other suitable type of force (or combination thereof). In one embodiment,
16 16 forces F_1 and F_2 may be programmable. Using programmable forces, packets may be
17 17 manipulated along arbitrarily chosen paths.

30 18 In the illustrated embodiment of Fig. 1, position sensor 23 may be operated with
19 19 various mechanisms to sense positions of packets 21. For instance, an optical imaging
20 20 system may be used to determine and monitor packet positions. Specifically, an optical
35 21 microscope may be connected to a CCD imaging camera, which may be interfaced with
22 22 an imaging card in a computer. The information from the imaging card may be processed
23 23 in the computer using image-analysis software. Alternatively, a CCD imaging device
40 24 may be incorporated in or above the reaction surface 12 to monitor the positions of
25 25 packets. Thus, positions of packets and their movement on reaction surface 12 may be
26 26 continuously monitored and recorded in the computer. A different mechanism of packet
27 27 position sensing uses electrical impedance measurements. The presence or absence of a
45 28 packet between two electrode elements may affect the electrical impedance between the

electrodes. Thus, measurement of electrical impedance between electrode elements may allow for indirect monitoring of packet positions.

In order to better understand the operation and design of the currently disclosed method and apparatus, which will be discussed first in relation to dielectrophoretic forces, it is useful to discuss dielectrophoretic theory in some detail. Such a discussion is aided by FIG. 2, which illustrates two packets, 21a and 21b, both being subjected to dielectrophoretic forces.

Dielectrophoretic forces may arise when a packet is placed in an inhomogeneous electrical field (AC or DC). In Fig. 2 the electrical field is weaker on the left side than on the right side. An electrical field induces electrical polarizations in the packet. The polarization charges are depicted at the two ends of the packets 21a and 21b along the field lines 35. Dielectrophoretic forces result from the interaction between the induced polarization (labeled as m_1 and m_2 in FIG. 2) and the applied inhomogeneous field. If a packet is suspended in a medium having different dielectric properties, such as a partitioning medium, then the packet may remain compartmentalized and may readily respond to manipulation forces against viscous drag. In a field of non-uniform strength, a packet may be directed towards either strong (packet 21a) or weak (packet 21b) electrical field regions, depending on whether the packet is more (packet 21a) or less (packet 21b) polarizable than a partitioning medium. In a field of non-uniform phase distribution (i.e. a traveling electrical field), a packet may be directed towards field regions of larger or smaller phase distribution, depending whether the packet has a longer or shorter dielectric response time than that of a partitioning medium.

DEP theory

When a packet of radius r , suspended in an immiscible medium of different dielectric properties, is subjected to an electrical field of frequency f , the polarization of the packet can be represented using an effective dipole moment (Wang *et al.*, "A Unified Theory of Dielectrophoresis and Traveling Wave Dielectrophoresis", Journal of Physics D: Applied Physics, Vol 27, pp. 1571-1574, 1994, incorporated herein by reference)

$$\vec{m}(f) = 4\pi\epsilon_m r^3 P_{CM}(f) \vec{E}(f) \quad (1)$$

where $\vec{m}(f)$ and $\vec{E}(f)$ are the dipole moment and field vectors in the frequency domain, $P_{CM}(f)$ is the so-called Clausius-Mossotti factor, given by

$$P_{CM}(f) = (\epsilon_d^* - \epsilon_m^*) / (\epsilon_d^* + 2\epsilon_m^*). \quad (2)$$

Here $\epsilon_i^* = \epsilon_i - j\sigma_i / (2\pi f)$ are the complex permittivities of the packet material ($k = d$) and its suspension medium ($k = m$), and ϵ and σ refer to the dielectric permittivity and electrical conductivity, respectively. Using the effective dipole moment method, the DEP forces acting on the packet are given by

$$\vec{F}(f) = 2\pi r^3 \epsilon_m \left(\text{Re}[P(f)] \nabla E_{rms}^2 + \text{Im}[P(f)] (E_{x0}^2 \nabla \varphi_{x0} + E_{y0}^2 \nabla \varphi_{y0} + E_{z0}^2 \nabla \varphi_{z0}) \right) \quad (3)$$

where $E(rms)$ is the RMS value of the field strength, E_{i0} and φ_{i0} ($i=x, y, z$) are the magnitude and phase, respectively, of the field components in a Cartesian coordinate frame. Equation (3) shows that the DEP force contains two independent terms. The first, relating to the real (in phase) part of the polarization factor $\text{Re}[P(f)]$ and to non-uniformities in the field *magnitude* (∇E_{rms}^2). Depending on the sign of $\text{Re}[P(f)]$, this force directs the packet either toward strong or weak field regions. The second term relates to the imaginary (out of phase) part of the polarization factor ($\text{Im}[P(f)]$) and to field phase non-uniformities ($\nabla \varphi_{i0}$, $i=x, y, z$) that correspond to the field traveling through space from large to small phase regions. Depending on the sign of $\text{Im}[P(f)]$, this directs packets toward regions where the phase values of the field components are larger or smaller.

Equations (1-3) indicate that the DEP phenomena have the following characteristics:

- (1) DEP forces experienced by packets are dependent on the dielectric properties of the packets (ϵ_d^*) and the partitioning medium (ϵ_m^*).

(2) The strong dependence of three-dimensional DEP forces on the field configuration allows for versatility in implementing dielectrophoretic manipulations.

DEP Forces on Packets

In one embodiment, a conventional dielectrophoresis component may be used for packet manipulation. In this case, the DEP force is given by

$$\bar{F}(f) = 2\pi r^3 \epsilon_m \operatorname{Re}[P(f)] \nabla E_{(rms)}^2 \quad (4)$$

where r is the packet radius, ϵ_m is the dielectric permittivity of the suspending fluid. $\operatorname{Re}[P(f)]$ is the real (in phase) part of the polarization factor and $\nabla E_{(rms)}^2$ is the field non-uniformity factor. For packets of water ($\epsilon = 78$ and $\sigma > 10^{-4}$ S/m) suspended in a hydrocarbon fluid ($\epsilon \sim 2$ and $\sigma \sim 0$), the factor $\operatorname{Re}[P(f)]$ is always positive and close to unity. Therefore, water packets are always attracted towards regions of large field strength. For example, if an electrode array composed of circular electrodes arranged in a hexagonal fashion is provided, water packets may be dielectrophoretically moved towards and trapped between, for example, an electrode pair, over a single electrode, or above a plurality of electrodes to which electrical signals are applied. Switching the electrical signals may result in movement of the DEP traps and may cause water packets to move in a chamber. Thus, packet manipulation may be realized by switching electrical signals applied to an electrode array so that DEP field traps are made "mobile" within a chamber.

Typical Forces and Velocities

For a water packet of 100 μm suspended in a hydrocarbon fluid such as decane, the DEP force may be on the order of 1000 pN if the field non-uniformity is $1.25 \times 10^{13} \text{ V}^2/\text{m}^3$ (equivalent to 5V RMS applied to an electrode pair of distance 50 μm with the field decaying to zero at 1000 μm). If the viscosity of the hydrocarbon fluid is small (0.838 mPa for Decane), the packet velocity may be of the order of 600 $\mu\text{m}/\text{sec}$, indicating that fast manipulation of packets is possible with electrode arrays. In the above

1 analysis, DEP force equation (4) has been used, which was developed for non-deformable
2 particles and holds well for suspended particles (such as cells, latex particles). Fluid
3 packets may be deformed under the influence of applied electrical field, affecting the
4 accuracy of equation (4) in describing DEP forces for packets. Nevertheless, equation
5 (4) should be generally applicable with some possible correction factors for different
6 packet shapes.

7 **FIG. 3** shows one possible implementation of position sensor 23 of **FIG. 2**.
8 Shown in **FIG. 3** are five impedance sensing electrodes 19, here illustrated as 19a, 19b,
9 19c, 19d, and 19e. Each sensing electrode 19 may be coupled to an impedance sensor 29,
10 here illustrated as impedance sensors 29a, 29b, 29c, and 29d. In one embodiment,
11 impedance sensing electrodes 19 may be positioned in operative relationship with surface
12 12 of fluidic device 10 in **FIG. 1**. For instance, sensing electrodes 19 may be placed on
13 or near surface 12. As packets 21 are manipulated about surface 12 by the application of
14 appropriate manipulation forces, impedance sensing electrodes 19 and sensors 29 may
15 sense a position of packets 21 by making one or more impedance measurements.

16 If the dielectric medium above an electrode is displaced by a packet having
17 different dielectric and/or conductive properties, the impedance detected at the electrode
18 element will change. Thus, one may determine the position of packets 21 by noting the
19 impedance measurements associated therewith. As is shown in **FIG. 3**, the impedance
20 between impedance sensing electrodes 19a and 19b is "high" (see impedance sensor 29d)
21 relative to, for instance, the impedance between impedance sensing electrodes 19b and
22 19c (see impedance sensor 29c). Thus, by pre-determining that the "high" impedance
23 value corresponds to the impedance due to the partitioning medium, it may be deduced
24 that some material of different impedance to the partitioning medium lies somewhere
25 between impedance sensing electrodes 19d and 19e and between 19b and 19c because the
26 impedance associated with those electrodes is "low" (see impedance sensor 29a). By
27 like reasoning, one may assume that no packet lies between impedance sensing electrodes
28 19c and 19d, for the impedance between those two electrodes is relatively "high" (see
29 impedance sensor 29b and 29c).

Those of skill in the art will appreciate that the "low" and "high" values discussed above may be reversed, depending upon the relative impedances of a packet and of a suspending medium. In other words, in some situations, a relatively "high" impedance measurement may signal the presence of a packet in between a pair of electrodes while a relatively "low" impedance may signal the lack of a packet. Those of skill in the art will also appreciate that individual impedance measurements may exhibit a wide range of values (not just "low" or "high"), and it may be possible to characterize different types and sizes of materials by noting their associated impedance measurements. For instance, one may be able to differentiate, by type, the two packets 21 of FIG. 3 by noting any differences in their impedance readings on impedance sensors 29a and 29c.

Impedance sensing may be based on the so-called mixture theory, which associates the impedance of a heterogeneous system with the dielectric properties of various system components and their volume fractions. Take a two-component, heterogeneous system where component 2 having complex dielectric permittivity ($\epsilon_2^* = \epsilon_2 - j \frac{\sigma_2}{2\pi f}$, f is the frequency) and a volume fraction α is suspended in component 1 having complex dielectric permittivity ($\epsilon_1^* = \epsilon_1 - j \frac{\sigma_1}{2\pi f}$). The complex permittivity of the total system is given by (Wang *et al.*, "Theoretical and experimental investigations of the interdependence of the dielectric, dielectrophoretic and electrorotational behavior of colloidal particles" in J. Phys. D: Appl. Phys. 26: 312-322, 1993, incorporated herein by reference)

$$\epsilon_{\text{sys}}^* = \epsilon_1^* \frac{\frac{1}{\alpha} + 2 \frac{\epsilon_2^* - \epsilon_1^*}{\epsilon_2^* + 2\epsilon_1^*}}{\frac{1}{\alpha} - \frac{\epsilon_2^* - \epsilon_1^*}{\epsilon_2^* + 2\epsilon_1^*}}$$

The total impedance of the system, which is assumed to have length L and cross-sectional area A , is given by

$$\Omega = \frac{L}{\omega \epsilon_{rs} A}$$

The electrical impedance between two electrode elements in the presence or absence of a packet may be analyzed using the above equations, with the parameters L and A determined experimentally. The existence of a packet may correspond to $\alpha > 0$ and the absence of a packet may correspond to $\alpha = 0$. From these equations, an impedance change would occur when a packet having different dielectric property (ϵ_2^*) from the partitioning media (ϵ_1^*) is introduced into the space between the two electrode elements.

A relatively low impedance measurement may indicate an obstruction or a packet (as is illustrated in FIG. 3) on or near surface 12. By determining impedance values, one may map locations of obstructions or packets relative to surface 12. In this way, one may generate a packet and/or obstruction distribution map with respect to reaction surface 12 of fluidic device 10. With the benefit of this disclosure, one of skill in the art will appreciate that the description associated with FIG. 3 may be implemented in many different ways. In particular, one may use any suitable type of impedance measurement devices known in the art to function with one or more electrodes. Such devices may include an impedance analyzer, a DC/AC conductance meter, or any circuit based upon methods of operation of these or other instruments having similar function.

FIG. 4 shows a three dimensional view of one embodiment of a fluidic device 10 according to the present disclosure. Fluidic device 10 includes reaction surface 12, an inlet port 14, an outlet port 16, driving electrodes 18, impedance sensing electrodes 19, connectors 20, and wall 22.

Reaction surface 12 provides an interaction site for packets. In one embodiment, reaction surface 12 may be completely or partially covered with a partitioning medium (not shown in FIG. 4) or other substance. In one embodiment, reaction surface 12 may be coated. In particular, for manipulation of aqueous packets in a hydrophobic partitioning medium, reaction surface 12 may include a hydrophobic coating, or layer,

5 1 having a hydrophobicity similar to or greater than the hydrophobicity of the partitioning
2 2 medium. Such a coating may prevent an aqueous packet from sticking, from spreading,
3 3 or from becoming unstable upon contact with reaction surface 12. Additionally, a coating
4 4 may modify association and/or interaction forces between packets and reaction surfaces to
10 5 facilitate manipulation of packets by appropriate manipulation forces. Further, a coating
6 6 may be used to reduce contamination of reaction surfaces by reagents in packets. Still
7 7 further, a coating may facilitate the deliberate adhesion, wetting, or sensing of packets at
15 8 or on reaction surfaces. If a dielectric layer coating is applied, the layer should be made
9 9 sufficiently thin to allow AC electric field penetration through the dielectric layer. In one
10 10 embodiment, the thickness of the layer may be between about 2 nm and about 1 micron.
11 11 In one embodiment, a hydrophobic coating may be Teflon that may be applied by means
20 12 known in the art such as sputtering or spin-coating. It is to be understood that any other
13 13 suitable coating that modifies an interaction between packets and the reaction surface may
14 14 be used.

25 15 Reaction surface 12 may be formed from a number of suitable materials. In the
16 16 illustrated embodiment, reaction surface 12 is a planar surface that has an upper surface
17 17 including driving electrodes 18 and impedance sensing electrodes 19. Although
30 18 illustrated as being coplanar with reaction surface 12, it is to be understood that driving
19 19 electrodes 18 and 19 may also be elevated or depressed with respect to reaction
20 20 surface 12. Likewise, reaction surface 12 need not be planar. Rather, it may have
21 21 concave or convex portions, or it may be deformed in some other manner. Reaction
35 22 surface 12 may be glass, silicon dioxide, a polymer, a ceramic, or any suitable electrically
23 23 insulating material. The dimensions of reaction surface 12 may vary widely depending on
24 24 the application but may be between about 20 microns by about 20 microns and about 50
40 25 centimeters by about 50 centimeters. More particularly, reaction surface 12 may be
26 26 between about 3 millimeters by about 3 millimeters and about 30 centimeters by about 30
27 27 centimeters.

45 28 Inlet port 14 may be adapted to inject or introduce materials onto reaction
29 29 surface 12 and may be any structure allowing ingress to reaction surface 12. In the

1 illustrated embodiment, inlet port 14 consists of an opening in wall 22. Such an opening
2 may be of any suitable size or shape. Alternatively, inlet port 14 may be a syringe needle
3 a micropipette, a tube, an inkjet injector, or any other suitable device able to inject a
4 material for introduction onto reaction surface 12. Using a micropipette or equivalent
5 device, wall 22 may not need to include any openings. Rather, material may be
6 introduced onto reaction surface 12 from above. A micropipette or any other equivalent
7 device may be attached to a micromanipulation stage (not shown in FIG. 4) so that
8 material may be precisely deposited onto specific locations of reaction surface 12. In one
9 embodiment, inlet port 14 may consist of a cylindrical tube opening onto reaction
10 surface 12. Such a tube may have a diameter of between about 1 micrometer and about 1
11 mm and, more particularly, between about 10 and 100 microns.

12 Outlet port 16 may be adapted to collect packets of material from reaction surface
13 12. Outlet port 16 may be any structure allowing egress from reaction surface 12. In the
14 illustrated embodiment, outlet port 16 consists of an opening in wall 22. The opening
15 may be of any suitable size or shape. Alternatively, outlet port 16 may be a micropipette
16 or any other equivalent device able to collect a material from reaction surface 12. Wall
17 22 may not need to include any openings. Rather, packets of material may be collected
18 from reaction surface 12 from above. A syringe or any other equivalent device may be
19 attached to a micromanipulation stage (not shown in FIG. 4) so that packets may be
20 precisely collected from specific locations on reaction surface 12. In one embodiment,
21 outlet port 16 may consist of a cylindrical tube opening onto reaction surface 12. Such a
22 tube may have a diameter of about 1 millimeter and a length of about 3 centimeters or
23 longer.

24 In one embodiment, inlet port 14 and outlet port 16 may be integral. For instance,
25 in the embodiment shown in FIG. 1 port 15 is a cylindrical tube opening onto reaction
26 surface 12. In alternative embodiments, one micropipette may serve as both an inlet port
27 and an outlet port. Alternatively, a single opening in wall 22 may serve both input and
28 output functions. In another embodiment, multiple inlet and outlet ports may be utilized.

1 Fluidic device 10 may include an arbitrary number of inlet and outlet ports. For
2 example, any one of the three unnumbered openings in wall 22, illustrated in FIG. 4, may
3 serve as an inlet port, an outlet port, or an integral inlet-outlet port, such as port 15 of
4 FIG. 1. In another embodiment, multiple inlet and/or outlet ports may extend completely
5 or partially along a wall 22 so that materials may be introduced and/or collected to and/or
6 from reaction surface 12. In such an embodiment, one may more precisely introduce or
7 collect materials.

8 In FIG. 4, driving electrode 18 is one of a number of other driving electrodes
9 arranged in an array upon reaction surface 12. In this embodiment, driving electrodes 18
10 may be associated with force generator 25 of FIG. 1, for the driving electrodes 18 may
11 contribute to the generation of forces, such as forces F_1 and F_2 of FIG. 1, to manipulate
12 packets of material on reaction surface 12 to promote, for instance, microfluidic
13 interactions.

14 Dielectrophoretic forces may be generated by an array of individual driving
15 electrodes 18 fabricated on an upper surface of a reaction surface 12. The driving
16 electrode elements 18 may be individually addressable with AC or DC electrical signals.
17 Applying an appropriate signal to driving electrode 18 sets up an electrical field that
18 generates a dielectrophoretic force that acts upon a packet, known to be at a certain
19 location through impedance measurements as described above in relation to FIG. 3.
20 Switching different signals to different electrodes sets up electrical field distributions
21 within fluidic device 10. Such electrical field distributions may be utilized to manipulate
22 packets in a partitioning medium.

23 In particular, the movement of packets under the influence of a manipulation force
24 may be controlled by switching appropriate electrical signals to different combinations of
25 driving electrodes 18. Specifically, the switching of electrical signals may initiate
26 different field distributions and generate manipulation forces that trap, repel, transport, or
27 perform other manipulations upon packets of material. By programmably switching
28 electrical signals to different combinations of driving electrodes 18 within an array,

5 1 electric field distributions and manipulation forces acting upon packets may be
2 2 programmable so that packets may be manipulated along arbitrarily chosen or
3 3 predetermined paths in a partitioning medium along reaction surface 12. Thus, packets
4 4 may be manipulated in an unlimited manner. Signals may be appropriately switched to
10 5 cause, for instance, a packet to move a single "unit distance" -- a distance between two
6 6 neighboring electrodes. Further, by programmably switching electrical signals, different
7 7 microfluidic reactions may be performed in series or in parallel. An electrode array
15 8 having such an ability to utilize programmable dielectrophoretic forces by programmed
9 9 switching of electrical signals to different combinations of driving electrodes 18 may be
20 10 termed a programmable dielectrophoretic array (PDA).

20 11 In FIG. 4, impedance sensing electrode 19 is one of a number of other impedance
12 12 sensing electrodes arranged in an array upon reaction surface 12. In this embodiment,
13 13 impedance sensing electrodes 19 may be associated with position sensor 23 of FIG. 1 and
25 14 is illustrated in FIG. 3. Impedance sensing electrodes 19 contribute to the sensing of
15 15 packet positions upon reaction surface 12 so that those packets of material may be
16 16 monitored and manipulated according to position.

30 17 In the illustrated embodiment, driving electrodes 18 and impedance sensing
18 18 electrodes 19 are electrodes of a two dimensional electrode array coupled to a top surface
19 19 of reaction surface 12. The size of the array may vary according to need, but in one
20 20 embodiment a 16 by 16 array is employed. Because fluidic device 10 is scaleable,
35 21 smaller or larger arrays may be fabricated without significant departure from the present
22 22 disclosure. For example, 256 by 256 arrays or larger may be made according to the
23 23 present disclosure. Driving electrodes 18 and impedance sensing electrodes 19 within an
40 24 array may be uniformly or non-uniformly spaced. The spacing may vary widely, but in
25 25 one embodiment, the spacing may be between about 2 microns and about 200 microns.
26 26 The electrodes may have different forms such as lines, squares, circles, diamonds,
27 27 polygons, or other suitable shapes. The dimensions of each electrode may vary, but a
45 28 typical electrode may be between about 0.2 microns and about 10 mm., and more
29 29 particularly, between about 1 micron and about 200 microns. Driving electrodes 18 and

1 impedance sensing electrodes 19 may be formed using any method known in the art. In
2 one embodiment, such electrodes may be formed using standard photolithography
3 techniques. For example, one may refer to, e.g., D. Qin *et al.*, "Microfabrication,
4 Microstructures and Microsystems", Microsystem Technology in Chemistry and Life
5 Sciences (Ed. Manz and Becker), Springer, Berlin, 1997, pp 1- 20, which is incorporated
6 herein by reference. Also, one may refer to Madou, Fundamentals of Microfabrication,
7 CRC Press, Boca Raton, 1997, which is incorporated herein by reference. Depending
8 upon the particular application, and the nature of the packets and partitioning medium,
9 the size and spacing of electrodes 18 and 19 may be smaller than, of similar size, or larger
10 than the diameters of the packets.

11 In one embodiment, impedance sensing electrodes 19 may be integral with driving
12 electrodes 18. In such an embodiment, the resulting array may be termed an integral
13 array. With an integral array, a single conductor coupled to reaction surface 12 may serve
14 both purposes -- driving packets and sensing positions of packets. Thus, a programmable
15 manipulation force may be generated upon packets upon reaction surface 12 and a
16 position of those packets may be sensed with a single electrode array.

17 In the embodiment of FIG. 4, wall 22 is adapted to enclose one or more sides of
18 reaction surface 12. It is to be understood that wall 22 may be any suitable structure
19 capable of enclosing one or more sides and/or the top of reaction surface 12. As
20 illustrated, wall 22 encloses four sides of reaction surface 12, defining an open reaction
21 surface chamber. In a most typical embodiment, the chamber may have a thickness of
22 between about 10 microns and about 20 millimeters. In another embodiment, wall 22
23 may enclose the top of reaction surface 12, forming a closed reaction chamber.

24 Wall 22 may be formed from any suitable material. In one embodiment, wall 22
25 may be made from machined plastic, aluminum, glass, plastic, ceramic, or any
26 combination thereof. In one embodiment, wall 22 may be partially or completely
27 transparent to certain wavelengths of radiation. Thus, radiation may be transmitted

1 through wall 22 to initiate or maintain certain microfluidic reactions or processes for
2 sensing. For instance, a photochemical reaction may be initiated through wall 22.

3 Connectors 20 of FIG. 4 may be adapted to provide electrical connections to
4 driving electrodes 18 and to impedance sensing electrodes 19. Connectors 20 may
5 provide electrical connections to an entire array of electrodes, or to preselected ones or
6 groups. In one embodiment, connectors 20 are coupled to a controller (not shown in
7 FIG. 4) that may adjust a programmable manipulation force distribution generated by
8 driving electrodes 18 according one or more packets position sensed with impedance
9 sensing electrodes 19. Thus, such a controller may effectively provide a feedback
10 mechanism between the driving electrodes 18 and the impedance sensing electrodes 19 --
11 The signals applied to driving electrodes 18 may be adjusted in view of one or more
12 results from the impedance sensing electrodes 19.

13 Turning now to FIG. 5, there is shown a side cross section view of a fluidic
14 device 10 according to the present disclosure. Fluidic device 10 includes a reaction
15 chamber 41 and an array of integral impedance sensing and driving electrodes, integral
16 array 43. In the illustrated embodiment, a control chip 60 is coupled to integral array 43.
17 Positioned upon a top surface of control chip 60 may be capillary wall 62 that forms a
18 lower surface of a capillary 64. Capillary 64 may lead to an inlet port 14 that leads into
19 chamber 41. Although illustrated with only one inlet port, it is contemplated that there
20 may be several such ports providing access to chamber 41. Above capillary 64 is a
21 substrate 66 that, in one embodiment, is made of glass although any suitable material
22 known in the art may be utilized instead.

23 In one embodiment, control chip 60 may be an integrated circuit configured to
24 control integrated array 43. Alternatively, control chip 60 may be a control interface
25 leading to another controlling device such as an integrated circuit, computer, or similar
26 device that may control integral array 43. Control chip 60 may utilize flip-chip
27 technology or any other suitable technique to establish electrical control over integral
28 array 43 by switching different signals to and from it.

FIG. 6 shows a controller 81 according to one embodiment of the presently disclosed method and apparatus. Controller 81 may include a computer 80, a signal generator 82, an electrode selector 84, a transducer 88, and a fluidic device 10 having a driving electrode 18 and an impedance sensing electrode 19.

Computer 80 may be configured to control fluidic device 10 and the fluid processing occurring upon reaction surface 12. Computer 80 may have a user interface that allows for simple programming of signal generator 82 and transducer 88, which measures impedance, to allow for programmable microfluidic processing. In particular, computer 80 may programmably control the initiation/termination of one or more signals from signal generator 82, the parameters of the one or more signals including frequencies, voltages, and particular waveforms, and control the switching of one or more signals from generator 82 to different combinations of electrodes 18 and 19.

Computer 80 may vary signals in many ways. For instance, one signal having a first frequency component may be sent through electrode selector 84 to a driving electrode 18 while another signal having a second, different frequency component may be sent to, for instance, an impedance sensing electrode 19 and through electrode selector 84. Any sequence of signals or combinations of signals may be sent different combinations of electrodes and from the fluidic device 10. Any signal parameter may be varied and any electrode selection may be controlled so that appropriate electric fields may be established at particular locations upon reaction surface 12. Alternating Current or Direct Current signals may be utilized.

Signal generator 82 may send a driving signal to one or more driving electrodes 18 while sending a sensing signal to one or more impedance sensing electrodes 19. In one embodiment, the driving signal and the sensing signal may comprise a single, composite processing signal having different frequency components. Such a signal may be used with an integrated array to provide (via a single processing signal) a frequency component to generate a programmable manipulation force and a frequency component to provide an impedance sensing signal. The manipulation and impedance sensing

1 components may also be combined by multiplexing or switching in time as is known in
2 the art.

3 In one embodiment, signal generator 82 provides one or more programmable
4 driving signals to one or more driving electrodes 18 through electrode selector 84 so that
5 a programmable alternating-current electric field, such as a non-uniform field, may be
6 produced at reaction surface 12. That electric field may induce polarization of packets of
7 materials adjacent to or in the vicinity of the one or more driving electrodes 18. A
8 programmable dielectrophoretic force distribution may, in this manner, be generated that
9 manipulates packets in a controllable, programmable manner so that varied
10 programmable fluidic interactions may take place upon reaction surface 12.

11 In one embodiment, signal generator 82 provides a sensing signal to one or more
12 impedance sensing electrodes 19 so that an impedance measurement may be made. The
13 impedance sensing signal may be applied to one or more pairs of impedance sensing
14 electrodes 19 and a change in voltage or current may be detected and transmitted to
15 computer 80 via sensing electrodes 88 and wire 86. Computer 80 may then compute the
16 impedance and hence, determine whether a packet or obstruction was present at or near
17 the pair(s) of impedance sensing electrodes 19 being probed.

18 In an embodiment utilizing a single integrated array (instead of separate
19 impedance sensing and driving electrode arrays, an integrated array utilizes electrodes
20 that function to both drive and sense packets), the integrated array may both generate a
21 programmable manipulation force and sense an impedance. In one approach, electrical
22 sensing signals for sensing electrode impedance may be applied at different frequencies
23 from driving signals for manipulation of packets. Summing signal amplifiers (not shown)
24 may be used to combine signals from sensing and driving electronics. By using a
25 frequency filter network (not shown), electrode impedance sensing signals may be
26 isolated from the driving signals. For example, a constant current at sensing frequency f_s
27 may be applied to integrated electrode pairs to be measured. The sensing electronics 88,
28 may then be operated at only the applied frequency f_s to determine a voltage drops across

1 the integrated electrode pairs, thus allowing the impedance at the sensing frequency f_s to
2 be derived without interference from the driving signals.

3 In another embodiment, driving signals may be used to monitor electrical
4 impedance directly. Driving signals may be switched to one or more integrated
5 electrodes to generate a force to manipulate or interact packets upon a reaction surface.
6 Simultaneously, an electrical current sensing circuit may be used to measure electrical
7 current going through the energized integrated electrodes. Electrode impedances may be
8 derived from such measurements of electrical current.

9 Although any suitable device may be used, in one embodiment a function
10 generator is used as signal generator 82. More particularly, an arbitrary waveform signal
11 generator in combination with voltage or power amplifiers or a transformer may be used to
12 generate the required voltages. In one embodiment, signal generator 82 may provide
13 sine-wave signals having a frequency up to the range of GHz and more particularly
14 between about 1 kHz and about 10 MHz and a voltage between about 1 V peak-to-peak
15 and about 1000 V peak-to-peak, and more particularly, between about 10 V peak-to-peak
16 and about 100 V peak-to-peak.

17 As illustrated, signal generator 82 may be connected to an electrode selector 84.
18 Electrode selector 84 may apply one or more signals from signal generator 82 to one or
19 more individual electrodes (impedance sensing electrodes and/or driving electrodes may
20 be individually addressable). Electrode selector 84 may be one of a number of suitable
21 devices including a switch, a multiplexer, or the like. Alternatively, electrode selector 84
22 may apply one or more signals to one or more groups of electrodes. In one embodiment,
23 selector 84 is made of electronic switches or a multiplexer. Selector 84 may be digitally-
24 controlled. With the benefit of this disclosure, those of skill in the art will understand
25 that selector 84 may be any suitable device that may programmably divert one or more
26 signals to one or more electrodes in any arbitrary manner.

27 As illustrated in FIG. 6, controller 81 provides a feedback loop mechanism from
28 impedance sensing electrodes 19 to driving electrodes 18 via computer 80, which itself is

5 1 coupled to signal generator 82, selector 84, and transducer 88. With the benefit of the
2 present disclosure, those of skill in the art will recognize that controller 81 may contain
3 more or fewer components. The feedback mechanism allows computer 80 to tailor its
4 commands to signal generator 82 according to positions of packets upon reaction surface
10 5 12, as determined by impedance sensing electrodes 19. Thus, controller 81 allows for the
6 adjustment of driving signals (and hence the adjustment of programmable manipulation
7 forces) according to positions of packets (as determined by impedance sensing electrodes
15 8 19). In embodiments utilizing an integral array of electrodes having integral impedance
9 sensing electrodes 19 and driving electrodes 18, a feedback mechanism may operate as
10 follows. Positions of packets may be determined by measuring impedances between
11 electrical elements by applying impedance sensing signals to the integral array. Position
20 12 information may then be used to control driving signals to the integral array to perform
13 microfluidic processing through the manipulation of packets. In one embodiment
14 computer 80 may be replaced by an application specific integrated circuit controller
25 15 (ASIC) designed specifically for the purpose.

16 FIG. 7 shows an electrode driver 94 according to an embodiment of the presently
17 disclosed method and apparatus. Driver 94 includes a computer 80, a signal generator 82,
30 18 a resistor network 100, a switching network 104, and a bitmap 108. Driver 94 is coupled
19 to fluidic device 10 which includes reaction surface 12 and an integral array 43.

20 Driver 94 may assist in the application of signals to integral array 43 in order to
35 21 direct microfluidic interactions of packets of material upon reaction surface 12. In one
22 embodiment, computer 80 directs signal generator 82 to apply an AC signal to integral
23 array 43. In the illustrated embodiment, from signal generator 82 there may be provided,
40 24 for example, eight increasing voltage amplitudes using resistor network 100, although
25 more or fewer voltage amplitudes may be used. The eight AC signals may be distributed
26 by switching network 104 via connection 106 to the integral array 43 according to a
27 bitmap 108 or according to any other suitable data structure stored in computer 80 or in
45 28 another device. By modifying bitmap 108 via computer 80, different voltage amplitudes
29 may be applied to different electrodes.

1 In one embodiment, signals to each electrode of integral array 43 may be
2 represented in bitmap 108 by 3 bits to address eight available voltage amplitudes.
3 Voltage amplitude distributions of bitmap 108 may be transmitted sequentially to
4 switching network 104 via connection 110 twelve bits at a time using a communication
5 protocol as is known in the art. In one embodiment, the communication protocol may use
6 the following convention. To address a single electrode of integral array 43, the first four
7 bits may specify the row of the array. The second four bits may specify the column of the
8 array. The next three bits may specify the desired voltage to be applied. The last bit may
9 be used for error control by parity check. The rows/column arrangement may be used for
10 different layouts of arrays. For instance, the row/column convention of addressing may
11 be used even for a hexagonal grid array configuration. Those skilled in the art will
12 appreciate that other methods may be used to address the electronic switching network
13 104 from computer 80.

14 FIG. 8 is side cross-section view of one embodiment of a fluidic device 10.
15 Fluidic device 10 includes a wall 22 which encloses the sides and top of a reaction
16 surface 12 to form a reaction chamber 41. Reaction surface 12 includes an integral array
17 43. Coupled to the integral array may be an interface board 54. Interface board 54 may
18 interface the integral array 43 with integrated circuits 50 via interconnect 55 and solder
19 bumps 52.

20 In the embodiment of FIG. 8, interface board 54 may be sandwiched between
21 chamber 41 and integrated circuits 50. On one side, interface board 54 may provide
22 electrical signals (AC or DC) to electrodes of integral array 43, while the other side of
23 interface board 54 may include pads for flip-chip mounting of integrated circuits 50.
24 Intermediate layers of interface board 54 may contain electrical leads, interconnects and
25 vias, such as interconnect 55 to transfer power and signals to and from electrodes of
26 integral array 43 and integrated circuits 50.

27 Interface board 54 may be fabricated using suitable PC-board and flip chip
28 technologies as is known in the art. Suitable silk-screened or electroplated flip-chip

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5 1 fluidic sensors 122 may be an electrochemical sensor that monitors the presence and
2 concentration of electroactive (redox-active) molecules in a packet solution. An
3 electrochemical sensor may take the form of two or more microelectrodes. In a three-
4 electrode configuration, for example, electrodes may correspond to working, reference,
10 5 and counter electrodes. A packet to be analyzed may be moved to be in contact with the
6 three electrodes. A voltage signal may be applied between the working and reference
7 electrode, and the current between the working and counter electrode may be monitored.
15 8 The voltage-current relationship allows for the determination of the presence or absence,
9 and concentration of electro-active molecules in the packet solution. Also attached to
10 PDA 116 may be suitable material injection and extraction devices 120 coupled to
11 appropriate inlet or outlet ports of PDA 116 (not shown in FIG. 10). Such devices may
20 12 be any suitable structure allowing ingress to and egress from PDA 116.

13 In electrical communication with PDA 116 may be PDA voltage drivers 126 and
14 dielectric position sensors 124. PDA voltage drivers 126 may be adapted to drive
25 15 electrodes within PDA 116 so that an electric field may be established that sets up
16 manipulation forces that manipulate one or more packets of material within PDA 116 to
17 promote microfluidic interactions. In one embodiment, PDA voltage drivers 126 may
30 18 include a signal generator and switching network as described in relation to FIG. 7.
19 Dielectric position sensors 124 may measure positions of packets within PDA 116. In
20 one embodiment, dielectric position sensors 124 may include measuring devices
35 21 connected to appropriate sensors that may determine a position of one or more packets of
22 material by sensing, for instance, a change in impedance between neighboring impedance
23 sensing electrodes within PDA 116 and by correlating that change in impedance with a
24 packet positioned adjacent the neighboring sensors according to the teachings of the
40 25 present disclosure.

26 Coupled to packet injection and extraction devices 120, PDA voltage drivers 126,
27 and dielectric position sensors 124 may be computer interface 128. Computer
45 28 interface 128 may be configured to allow host computer 130 to interact with PDA 116. In

1 one embodiment, computer interface 128 may be a digital or analog card or board that
2 may analyze impedance data to obtain a packet distribution map.

3 In the embodiment of FIG. 10, host computer 130 may be coupled to computer
4 interface 128 to provide for control of PDA 116. Host computer 130 may be coupled to
5 position tracking agent 132 and to low-level control agent 134. Position tracking agent
6 132 may be adapted to store, process, and track positions of packets within the fluidic
7 processor PDA 116. Low-level control agent 134 may be configured to provide
8 instructions to host computer 130 from library interface 136 and software interface 138.
9 Library interface 136 may hold various sets of subroutines for programmably
10 manipulating packets of materials on PDA 116. Software interface 138 that may allow
11 for custom programming of instructions to be executed by the fluidic processor PDA 116
12 to programmably manipulate packets. Alternatively established programs of
13 manipulation instructions for specific fluid processing tests may be read from stored data
14 and executed by the PDA fluid processor 116.

15 FIG. 11 illustrates operation of the presently disclosed method and apparatus. In
16 FIG. 11, open squares represent electrodes of an integral array. However, it is
17 contemplated that the description below applies equally well to a device utilizing separate
18 impedance sensing electrodes and driving electrodes.

19 In the illustrated embodiment, a packet 21a may be introduced onto reaction
20 surface 12 adjacent the location represented by integral impedance sensor/electrode 201.
21 The packet may be compartmentalized in an immiscible partitioning medium (not
22 shown). The introduction of the packet may be accomplished using an appropriate inlet
23 port positioned adjacent to electrode 201. Alternatively, a packet may be introduced
24 adjacent electrode 201 by applying an appropriate signal to electrode 201 to generate an
25 extraction force that may extract the packet from an inlet port or from an injector directly
26 onto reaction surface 12 and adjacent to electrode 201.

27 Once positioned upon reaction surface 12, packet 21a may be made to move along
28 a predetermined path indicated by dashed line 250. A path may be specified in a number

1 of different ways. In one embodiment, a user may specifically define a path. For
2 instance, one may specify a path, through appropriate programming of a controller or
3 processing system, such as the one depicted numeral 250. Alternatively, a user may
4 specify a starting position and an ending position to define a path. For instance, a user
5 may specify that packet 21a is to be introduced adjacent electrode 201 and end at a
6 location adjacent electrode 215. Alternatively, one may specify a starting and ending
7 location with specific path information in between. For instance, a user may specify a
8 starting position, an ending position, and a wavy path in between. As can be seen from
9 FIG. 11, the path may have any arbitrary shape and it may be programmed in any number
10 of ways.

11 To move packet 21a generally along the path, electrical signals may be suitably
12 switched to integral impedance sensors/electrode pairs so that programmable
13 manipulation forces may be created that act upon packet 21a to propel it generally along
14 the specified path. As discussed earlier, the signals may be varied in numerous ways to
15 achieve the proper manipulation force. In the illustrated embodiment, applying voltage
16 signals to electrode pairs 202 and 203 may create an attractive dielectrophoretic force that
17 moves packet 21a from electrode 201 towards electrode 203 generally along path 250.
18 As packet 21a moves generally along a specified path, the integral array may measure
19 impedances to map the position of the packet upon reaction surface 12. Knowing the
20 position of a packet allows manipulation forces to be directed at appropriate positions to
21 achieve a desired microfluidic processing task or interaction. In particular, knowing a
22 position of a packet allows an appropriate signal to be switched to an appropriate
23 electrode or electrode pair to generate a manipulation force that further propels or
24 interacts the packet according to one or more instructions.

25 As packet 21a moves from electrode 201 towards electrode 203, the impedance
26 between electrode 202 and electrode 203 may change value, indicating that packet 21a is
27 between, or partially between, those two electrodes. The impedance may be measured as
28 described in FIG. 3. A controller or processing system (not shown in FIG. 11) may
29 register the location of packet 21a and may apply a signal, for instance, to electrode pairs

5 1 **204** and **205**, creating an attractive dielectrophoretic force which propels packet **21a**
2 towards those electrodes generally along path **250**. As the impedance between electrode
3 **204** and electrode **205** changes value, a controller or processing system may apply a
4 signal to electrodes **206** and **207** to propel packet **21a** along path **250**. As packet **21a**
10 5 continues along path **250**, the impedance between electrode **206** and electrode **207** may
6 change value, indicating the presence of packet **21a** adjacent that location along the array.
7 Thus, as packet **21a** moves along path **250**, a controller or processing system may
15 8 constantly monitor the position of the packet by measuring impedance between electrode
9 pairs and adjust electrical signals to an appropriate electrode or electrode pair (and hence,
10 adjust manipulation forces) to continue to propel the packet further along the specified
11 path.

20 12 Measuring an impedance between pairs of electrodes not only allows a position of
13 a packet to be determined, but it also allows for the determination of a location of an
25 14 obstruction or blockage upon reaction surface **12**. For example, measuring the impedance
15 between electrodes **211** and **213** may indicate the presence of obstruction **212**. By noting
16 the position of obstruction **212**, a controller or processing system may re-route one or
17 more packets around the obstruction so that no interference with microfluidic processing
30 18 interactions occurs. For example, if a path is specified that passes through an area
19 occupied by obstruction **212**, a controller or processing system may modify electrical
20 signals to propel a packet generally along the specified path while avoiding the
35 21 obstruction. For instance, a stronger or weaker signal may be sent to one or more
22 electrodes or electrode pairs near obstruction **212** to steer a packet clear of the blockage
23 while still maintaining, generally, the path that was originally specified, and more
24 particularly, the originally specified end point

40 25 A controller or processing system according to the presently disclosed method and
26 apparatus may be programmed to scan for several obstructions and/or packets. Such a
45 27 scan may build up a distribution map, showing the location(s) of various packets and/or
28 obstructions on an entire reaction surface **12** or a portion thereof. Such a distribution map
29 may be a virtual map, stored, for example, in a computer memory or display. Turning

again to **FIG. 11**, impedances of all electrode pairs adjacent to path 250 may be measured to determine if an obstruction blocks that path or if a packet lies somewhere in that area. If the path is determined to be clear (e.g., if all the electrode pairs show an impedance value indicating a clear area), a packet may be safely propelled generally along the path while avoiding any interactions with other packets and/or obstructions. However, if an obstruction is discovered, several different actions may be taken. In one embodiment, the user may be notified that a blockage exists along the specified path. The user may then specify a different path or give another appropriate instruction. In another embodiment, the controller or processing system may determine if the obstruction may be avoided while still maintaining generally the same specified path. If possible, electrical signals may be modified and delivered to an electrode or electrode pairs to generate appropriate electrical field distributions that set up proper manipulation forces that will aid in avoiding the obstruction. Because, at least in part, of this ability to constantly measure positions and responses of packets during manipulation, a controller or processing system may be capable of monitoring the integrity of fluidic processing, reporting and correcting any errors that may occur.

FIG. 11 also depicts how processing may be carried out on two packets. In the illustrated embodiment, a second packet 21b begins on reaction surface 12 near electrode 217. A second path, path 260, may be specified that ends at electrode 219. As can be seen, paths 250 and 260 may cross at interaction point 240. At interaction point 240, the two packets may interact in many ways as illustrated, for example, in **FIG. 12**. The interaction may include, but is not limited to, fusing, merging, mixing, reacting, dividing, splitting, or any combination thereof. For instance, the two packets may interact at interaction point 240 to form one or more intermediate or final reaction products. Those products may be manipulated in the same or in a similar manner as the two original packets were manipulated.

FIG. 11 also depicts how maintenance may be performed upon reaction surface 12. A maintenance packet 21c adapted to perform maintenance upon reaction surface 12 may be introduced onto reaction surface 12 by a maintenance port (not shown

1 in FIG. 11). A maintenance port may be similar to an inlet port in structure but may be
2 dedicated to the introduction of one or more maintenance packets 21c designed
3 specifically, for instance, to clean or maintain reaction surface 12, a surface coating, or
4 one or more electrodes or sensors. Maintenance packet 21c may also react with an
5 obstruction in such a way as to remove that obstruction. As illustrated, maintenance
6 packet 21c may begin near electrode 241. It may then be propelled along path 270,
7 providing maintenance, perhaps, to electrodes 242 and 243. Maintenance packet 21c may
8 be propelled back to a maintenance port, extracted from reaction surface 12, and later
9 used again, or it may be discarded at an outlet part.

10 FIG. 12 demonstrates several different possible fluidic interactions that may be
11 carried out using the presently disclosed method and apparatus. In the illustrated
12 embodiment, packets 21 (only one is labeled for convenience) reside upon a reaction
13 surface 12 having an integral array 43 (only one electrode is labeled for convenience). In
14 the top pane of FIG. 12, there is shown an interaction in which a single packet is
15 manipulated on the reaction surface by moving the packet in a programmed fashion. In
16 the middle pane, two packets, starting at different locations upon the reaction surface, are
17 directed, via appropriate electrical signals, to come together at a specified location (near
18 the center of the array) to fuse together, for example, to initiate a reaction. The fused
19 packet may be manipulated just as the original packets were manipulated. For instance,
20 the fused packet may be moved to various locations or it may fuse again with another
21 packet(s). Shown in the bottom pane of FIG. 12 is a splitting interaction. As shown, a
22 single packet is subjected to different programmable manipulation forces that cause the
23 packet to split into two distinct packets. Such an interaction may be accomplished by,
24 first, noting the position of the packet to be split, and then by applying appropriate signals
25 to electrode pairs to generate two or more opposing forces that cause the packet to split
26 apart.

27 FIG. 13 is a flowchart showing one embodiment of a method of operation. A
28 material may be introduced onto a reaction surface and compartmentalized to form one or
29 more packets in step 300. Multiple materials may be introduced at different locations

1 along reaction surface 12 to form a plurality of packets. A path may be specified as in
 2 step 310. The path may be designed to accomplish any type of microfluidic processing,
 3 manipulation, or interaction. Different reactions may be performed in serial or in parallel
 4 according to different paths. Instructions governing such processing may be embodied in
 5 the pseudo-code that may be routed through computer interface 128 of FIG. 10.
 6 Illustrative code may read as follows:

7 Example: AvidinActin.PSL

8 Use inlet(1-3), outlet(1-2)
 9 Inlet(1) is actin
 10 Inlet(2) is avidin
 11 Inlet(3) is enzyme
 12 Outlet(1) is polymer
 13 Outlet(2) is waste
 14 Matrix(1,2) is accumulator
 15 Clean
 16 Do
 17 Sactin = (Pull actin) // pull a new packet on the next
 18 Savidin = (Pull avidin) // available matrix element next to
 19 Senzyme = (Pull enzyme) // the inlets
 20 Move Sactin into accumulator // merges components and enzyme
 21 Move Savidin into accumulator // in a single packet
 22 Move Senzyme into accumulator
 23 Wait 1000ms
 24 ShiftRow accumulator.row ,+1 // drag packet left into polymer outlet
 25 Move 0.5*accumulator into (2, accumulator.column)// drag half packet to row 2
 26 ShiftRow 2, + 1 // drag packet left into waste
 27 Loop Until polymer.count = 10 // number of packet at polymer outlet = 10
 28 Clean

29 In step 315, computer 80 of FIG. 6 or any other suitable device may determine
 30 the next unit step along the path specified in step 315. In other words, a path may be
 31 broken down into unit steps and the next unit step or steps may be determined with
 32 respect to the specified path. In step 320, a programmable manipulation force is
 33 generated on reaction surface 12 through the use of any of the mechanisms disclosed
 34 herein. The programmable manipulation force may manipulate the one or more packets
 35 according to instructions from a user. In step 330, the response(s) of the one or more
 36 packets may be monitored. This step may include measuring an impedance on the
 37 reaction surface as discussed herein. In particular, one may determine whether the one or

1 more packets moved to where they were supposed to, or whether they interacted as
2 instructed. In step 340, it may be determined if the packet movement was successful --
3 that is, it may be determined whether the packet ended up at a location corresponding to
4 the unit step determined in step 315.

5 If a packet movement was successful (i.e., if the packet responded correctly to the
6 programmable manipulation force(s)), then it may be determined, by comparison with the
7 specified path, whether or not the packet destination has been reached. In other words, it
8 may be determined if the packet has moved to the end location of the specified path. If
9 the destination has not been reached, the next unit step movement may be determined at
10 step 315 and steps 320, 330, 340, and 365 may be repeated. If the destination has been
11 reached, it may be determined whether another packet is to be manipulated in step 370.
12 This step may include a user prompt. If no further packets are to be manipulated, it may
13 be determined whether fluidic processing is complete in step 380. If yes, the process may
14 be ended at step 390. Step 390 may include the collecting of one or more packets, further
15 analysis, throwing away of the reaction surface, or any procedure described herein. If the
16 processing is not complete, the next step of processing may be determined in step 395.
17 The next step may entail, for example, the introduction of another packet, the
18 specification of another path, or any other step of FIG. 13.

19 If a packet manipulation is unsuccessful (i.e., if the applied programmable
20 manipulation force(s) did not produce a desired interaction or movement along a
21 specified path as indicated by step 340), one may locate an obstruction upon the reaction
22 surface as indicated in step 350 and as taught herein. After locating any obstructions, a
23 new, modified path may be determined or specified as indicated by step 360, leading to
24 step 310.

25 As mentioned with relation to FIG. 1, the present disclosure contemplates that
26 many different types of forces may be utilized as a manipulation force for promoting
27 fluidic interactions among packets of material on a reaction surface. Specifically, suitable
28 forces other than dielectrophoresis include electrophoretic forces, optical forces,

1 mechanical forces, or any combination thereof. Below are discussed embodiments of the
2 present disclosure dealing with electrophoretic and optical manipulation forces.

3 *Programmable Electrophoretic Array (PEA)*

4 A fluidic processing system incorporating a programmable electrophoretic array
5 may be constructed according to the present disclosure. As used herein, "programmable
6 electrophoretic array" (PEA) refers to an electrode array whose individual elements can
7 be addressed with DC, pulsed, or low frequency AC electrical signals (typically, less than
8 about 10 kHz) electrical signals. The addressing of electrode elements with electrical
9 signals initiates different field distributions and generates electrophoretic manipulation
10 forces that trap, repel, transport or perform other manipulations upon charged packets on
11 and above the electrode plane. By programmably addressing electrode elements within
12 the array with electrical signals, electric field distributions and electrophoretic
13 manipulation forces acting upon charged packets may be programmable so that packets
14 may be manipulated along arbitrarily chosen or predetermined paths. A PEA may utilize
15 electrophoretic forces in DC or low-frequency (typically, less than about 10 kHz) AC
16 electrical fields. Such electrophoretic forces may be used instead of, or in addition to,
17 another manipulation forces such as dielectrophoresis.

18 Negative or positive charges may be induced or injected into fluid packets. The
19 charged packets may be moved or manipulated by electrophoretic forces generated by an
20 electrode array fabricated on an inner surfaces of a chamber in accordance with this
21 disclosure. The electrode array, termed a programmable electrophoretic array (PEA),
22 may consist of uniformly or non-uniformly spaced electrode elements. Individual
23 electrode elements may be independently addressable with DC, pulsed, or low frequency
24 AC electrical signals (< about 10 kHz). Characteristic dimensions of individual electrode
25 elements may be of any size but, in one embodiment, may lie between 0.2 micron and 10
26 mm. Individual electrode elements may take similar or different geometrical forms such
27 as squares, circles, diamonds, or other shapes. Programmably switchable electrical
28 signals may be applied to individual electrode elements so that a programmable electrical
29 field distribution may be generated. Such a distribution may impose electrophoretic

1 forces to trap, repel, transport or manipulate charged packets in a partitioning medium.
2 Further, electrical signals may be applied to such an array so that a packet may be broken
3 down to two or more packets. The programmability of a PEA may be reflected in the fact
4 that the electric field distributions and electrophoretic forces acting on charged packets
5 may be programmable so that charged packets may be trapped or repelled or transported
6 along arbitrarily chosen paths in the partitioning medium, and that a PEA may be
7 programmed to perform different reactions in series or in parallel where different
8 manipulation protocols of packets (differing in size, number, and/or reagent type
9 concentration) may be required. As with PDA surface modification, if a dielectric layer
10 coating is applied to the surface of a PEA to modify interaction forces between packets
11 reaction surfaces, the dielectric layer may be made sufficiently thin (typically 2 nm to 1
12 micron) to allow for electric field penetration.

13 *Optical Manipulation*

14 Optical tweezers (which may consist of a focused laser beam with a light intensity
15 gradient) may be also be used for trapping and manipulating packets of material. Optical
16 manipulation requires that the refractive indices of the packets be different from that of
17 their suspending medium, for instance, a partitioning medium as described herein. As
18 light passes through one or more packets, it may induce fluctuating dipoles. Those
19 dipoles may interact with electromagnetic field gradients, resulting in optical forces
20 directed towards or away from the brighter region of the light. If their refractive indices
21 are higher than that of the partitioning medium, packets may be trapped in a bright
22 region, and when the laser light moves with respect to the partitioning medium, packets
23 may follow the light beam, allowing for optical manipulation forces. Conversely, if the
24 packets have refractive indices smaller than their partitioning medium, they will
25 experience forces directing them away from bright regions.

26 Therefore, if packets have different refractive indexes from that of the partitioning
27 medium (e.g., water packets in air or oil), optical tweezers may exert forces on them.
28 Therefore, to manipulate and interact packets, a microscope or other optical system
29 incorporating one or more laser tweezers may be used. A chamber containing a

1 partitioning medium in accordance with the present disclosure may be placed into such an
2 optical system. Following the introduction of packets of material into the chamber, laser
3 tweezers may be used to trap packets. By moving the focal point of the optical tweezers
4 with respect to the partitioning medium (e.g., moving a stage holding the thin chamber
5 containing the partitioning medium whilst fixing the position of laser tweezers and/or by
6 focusing the laser beam to different depths in the partitioning medium), packets may be
7 manipulated as described herein. Through the use of apparatus such as a computer-
8 controllable, multi-axis translation stage, the movement of the optical tweezers with
9 respect to the suspending medium may be programmed or automatically controlled. Thus
10 the optical tweezer may be moved, with respect to the medium, along any arbitrarily
11 chosen or predetermined paths. By doing so, packets under the influences of the optical
12 tweezers may be manipulated along any arbitrarily chosen or predetermined paths.

13 Example 1

14 Aqueous materials have been compartmentalized to form packets using
15 hydrophobic liquids as a partitioning medium. Partitioning mediums so used have
16 included decane, bromodocane, mineral oil, and 3 in 1™ oil. Packets have been formed
17 by briefly sonicating about 3 milliliters of the hydrophobic liquid to which had been
18 added 20 to 50 microliters of aqueous medium. Aqueous media tested have included
19 deionized water, tap water (electrical conductivity of about 40 mS/m) and phosphate
20 buffered saline (PBS) solution.

21 Example 2

22 Aqueous packets suspended in mineral oil, bromodocane and 3 in 1™ oil have
23 been collected by dielectrophoresis by applying sinusoidal signals to gold-on-glass
24 electrode arrays having 20, 80 and 160 micron spacing, respectively. The 20-micron
25 electrode array consisted of parallel line electrodes (20 microns in width and spacing).
26 The 80 and 160 micron electrode arrays were of the interdigitated, castellated geometries.
27 Aqueous packets were collected at electrode edges or tips when AC voltage signals

1 between 100 Hz and 20 MHz were applied. Applied voltages were from 10 to 100 V
2 peak-to-peak. The formation of pearl-chains of water packets has also been observed.

3 Example 3

4 Aqueous packets in hydrophobic suspension have been brought together and fused
5 under the influence of dielectrophoretic forces on the same electrode arrays used in
6 Example 2.

7 Example 4

8 Packets have been moved from one electrode element to another under influence
9 of dielectrophoretic forces when the AC electrical field is switched on an addressable
10 array of parallel line electrodes having 20 micron width and spacing.

11 Example 5

12 Sensitive AC impedance monitors have been built for use with microelectrode
13 arrays. Such monitors may provide for sensitive dielectric sensing of packet positions.

14 While the present disclosure may be adaptable to various modifications and
15 alternative forms, specific embodiments have been shown by way of example and
16 described herein. However, it should be understood that the present disclosure is not
17 intended to be limited to the particular forms disclosed. Rather, it is to cover all
18 modifications, equivalents, and alternatives falling within the spirit and scope of the
19 disclosure as defined by the appended claims. Moreover, the different aspects of the
20 disclosed apparatus and methods may be utilized in various combinations and/or
21 independently. Thus the invention is not limited to only those combinations shown
22 herein, but rather may include other combinations.

Claims

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WHAT IS CLAIMED IS:

1. An apparatus for programmably manipulating a packet, said apparatus comprising:
 - a reaction surface configured to provide an interaction site for said packet;
 - an inlet port coupled to said reaction surface and configured to introduce said packet onto said reaction surface;
 - means for generating a programmable manipulation force upon said packet to programmably move said packet about said reaction surface along arbitrarily chosen paths; and
 - a position sensor coupled to said reaction surface and configured to sense a position of said packet on said reaction surface; and
 - a controller coupled to said means for generating a programmable manipulating force and to said position sensor, said controller configured to adjust said programmable manipulation force according to said position.
2. The apparatus of claim 1, further comprising an outlet port coupled to said reaction surface and configured to collect said packet from said reaction surface.
3. The apparatus of claim 1, wherein said means for generating a manipulation force comprises a conductor adapted to generate an electric field.
4. The apparatus of claim 1, wherein said means for generating a manipulation force comprises a light source.
5. The apparatus of claim 1, wherein said manipulation force comprises a dielectrophoretic force, an electrophoretic force, an optical force, a mechanical force, or any combination thereof.
6. The apparatus of claim 1, wherein said position sensor comprises a conductor configured to measure an electrical impedance of said packet.

5 1 7. The apparatus of claim 1, wherein said position sensor comprises an optical system
2 2 configured to monitor said position of said packet.

10 4 8. The apparatus of claim 1, wherein said means for generating a programmable
5 5 manipulation force and said position sensor are integral.

15 7 9. An apparatus for microfluidic processing by programmably manipulating packets, said
8 8 apparatus comprising:

9 9 a reaction surface configured to provide an interaction site for said packets;

10 10 an inlet port coupled to said reaction surface and configured to introduce said
11 11 packets onto said reaction surface;

20 12 an array of driving electrodes coupled to said reaction surface and configured to
13 13 generate a programmable manipulation force upon said packets to direct
14 14 said microfluidic processing by moving said packets along arbitrarily
25 15 chosen paths; and

16 16 an array of impedance sensing electrodes coupled to said reaction surface and
17 17 configured to sense a position of said packets during said microfluidic
18 18 processing.

30 19
20 20 10. The apparatus of claim 9, further comprising an outlet port coupled to said reaction
21 21 surface and configured to collect said packets from said reaction surface.

35 22
23 23 11. The apparatus of claim 9, further comprising a controller coupled to said array of
24 24 driving electrodes and to said array of impedance sensing electrodes, said controller
25 25 adapted to provide a feedback from said array of impedance sensing electrodes to said
40 26 array of driving electrodes.

27
28 28 12. The apparatus of claim 9, wherein said array of driving electrodes and said array of
45 29 impedance sensing electrodes are integral.

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1 13. The apparatus of claim 9 further comprising an integrated circuit coupled to said
2 array of driving electrodes and to said array of impedance sensing electrodes.

3
4 14. The apparatus of claim 9 further comprising a coating modifying a hydrophobicity of
5 said reaction surface.

6
7 15. The apparatus of claim 9, further comprising a maintenance port.

8
9 16. An apparatus for processing packets in a partitioning medium, said apparatus
10 comprising:

11 a chamber configured to contain said packets and said partitioning medium;

12 a programmable dielectrophoretic array coupled to said chamber and configured
13 to generate a programmable dielectrophoretic force to direct processing of
14 said packets; and

15 an impedance sensing array of electrodes integral with said programmable
16 dielectrophoretic array, said impedance sensing array of electrodes
17 configured to sense a position of said packets within said chamber.

18
19 17. The apparatus of claim 16, further comprising an integrated circuit coupled to said
20 programmable dielectrophoretic array and to said impedance sensing array of electrodes.

21
22 18. The apparatus of claim 16, further comprising a controller coupled to said
23 programmable dielectrophoretic array and to said impedance sensing array of electrodes,
24 said controller adapted to provide a feedback from said impedance sensing array of
25 electrodes to said programmable dielectrophoretic array.

26
27 19. The apparatus of claim 16, wherein said electrodes are between about 1 micron and
28 about 200 microns and are spaced between about 1 micron and about 200 microns.

29
30 20. A method for manipulating a packet, comprising:

5 1 providing a reaction surface, an inlet port coupled to said reaction surface, means
2 2 for generating a programmable manipulation force upon said packet, a
3 3 position sensor coupled to said reaction surface, and a controller coupled
4 4 to said means for generating a programmable manipulation force and to
10 5 said position sensor;

6 6 introducing a material onto said reaction surface with said inlet port;

7 7 compartmentalizing said material to form said packet;

15 8 sensing a position of said packet with said position sensor;

9 9 applying a programmable manipulation force on said packet at said position with
10 10 said means for generating a programmable manipulation force, said
11 11 programmable manipulation force being adjustable according to said
20 12 position by said controller;

13 13 programmably moving said packet according to said programmable manipulation
14 14 force along arbitrarily chosen paths.

25 15
16 16 21. The method of claim 20, wherein said packet comprises a fluid packet, an
17 17 encapsulated packet, or a solid packet.

30 18
19 19 22. The method of claim 20, wherein said compartmentalizing comprises suspending
20 20 said material in a partitioning medium.

35 21
22 22 23. The method of claim 22, wherein said material is immiscible in said partitioning
23 23 medium.

40 24
25 25 24. The method of claim 22, wherein said reaction surface includes a coating, and a
26 26 hydrophobicity of said coating is greater than a hydrophobicity of said partitioning
27 27 medium.

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5 1 25. The method of claim 20, wherein said applying a programmable manipulation force
2 comprises applying a driving signal to one or more driving electrodes arranged in an array
3 to generate said programmable manipulation force.

10 5 26. The method of claim 20, wherein said programmable manipulation force comprises a
6 dielectrophoretic force, an electrophoretic force, an optical force, a mechanical force, or
7 any combination thereof.

15 8 27. The method of claim 20, wherein said sensing a position comprises applying a
9 sensing signal to one or more impedance sensing electrodes arranged in an array to detect
10 an impedance associated with said packet.

20 12 28. The method of claim 20, further comprising interacting said packet, wherein said
13 interacting comprises moving, fusing, merging, mixing, reacting, metering, dividing,
14 splitting, sensing, collecting, or any combination thereof.

25 16 29. A method of fluidic processing, said method comprising:
17

30 18 providing a reaction surface, an inlet port coupled to said reaction surface, an
19 array of driving electrodes coupled to said reaction surface, and an array of
20 impedance sensing electrodes coupled to said reaction surface;

21 introducing one or more materials onto said reaction surface with said inlet port;

35 22 compartmentalizing said one or more materials to form a plurality of packets;

23 applying a sensing signal to one or more of said impedance sensing electrodes to
24 determine a position of one or more of said plurality of packets; and

40 25 applying a driving signal to one or more of said driving electrodes to generate a
26 programmable manipulation force on one or more of said plurality of
27 packets at said position; and

45 28 interacting one or more of said plurality of packets according to said
29 programmable manipulation force.
30

5 1 30. The method of claim 29, wherein at least one of said plurality of packets comprises a
2 fluid packet, an encapsulated packet, or a solid packet.

10 4 31. The method of claim 29, wherein said sensing signal and said driving signal
5 comprise a single processing signal.

15 7 32. The method of claim 31, wherein said processing signal comprises a first frequency
8 component corresponding to said sensing signal and a second frequency component
9 corresponding to said driving signal.

20 11 33. The method of claim 29, further comprising forming a packet distribution map
12 according to said positions of said plurality of packets.

25 14 34. The method of claim 29, further comprising determining a position of one or more
15 obstructions on said reaction surface.

30 17 35. The method of claim 29, wherein said interacting comprises moving, fusing,
18 merging, mixing, reacting, metering, dividing, splitting, sensing, collecting, or any
19 combination thereof.

35 21 36. A method for manipulating one or more packets on a reaction surface, comprising:
22 providing a programmable dielectrophoretic array coupled to said reaction surface
23 and an impedance sensing array of electrodes integral with said
24 programmable dielectrophoretic array;
25 introducing a material onto said reaction surface;
40 26 compartmentalizing said material to form said one or more packets;
27 specifying a path upon said reaction surface;
28 applying a programmable manipulation force with said programmable
45 29 dielectrophoretic array on said one or more packets to move said one or
30 more packets along said path;

1 sensing a position of said one or more packets with said impedance sensing array
2 of electrodes;
3 monitoring whether said position corresponds to said path; and
4 interacting said one or more packets.

5
6 37. The method of claim 36, wherein at least one of said one or more packets comprises
7 a fluid packet, an encapsulated packet, or a solid packet.

8
9 38. The method of claim 36, further comprising:
10 sensing a position of an obstruction;
11 determining a modified path, said modified path avoiding said obstruction; and
12 applying a programmable manipulation force on said one or more packets to move
13 said one or more packets along said modified path.

14
15 39. The method of claim 36, wherein said specifying a path comprises specifying an
16 initial position and a final position.

17
18 40. The method of claim 36, wherein said introducing a material comprises extracting
19 said material with a dielectrophoretic extraction force from an injector onto said reaction
20 surface.

21
22 41. The method of claim 36, wherein said interacting comprises moving, fusing,
23 merging, mixing, reacting, metering, dividing, splitting, sensing, collecting, or any
24 combination thereof.

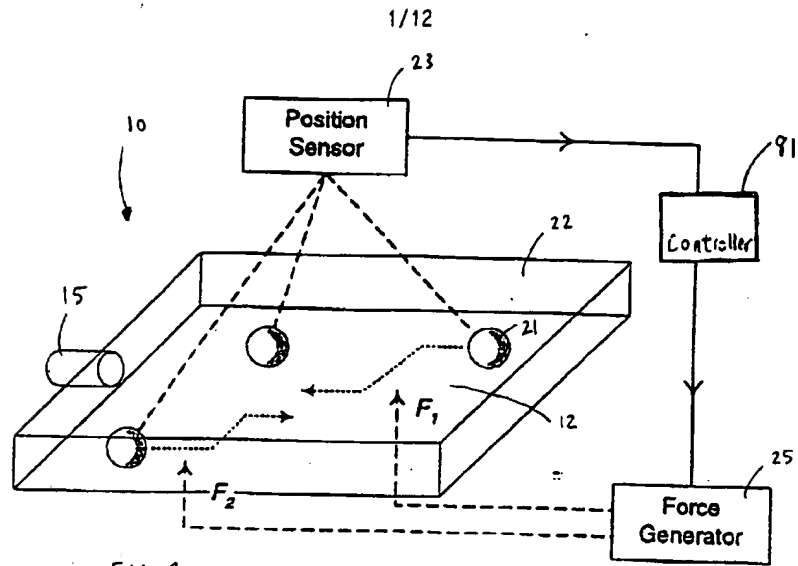


Fig. 1

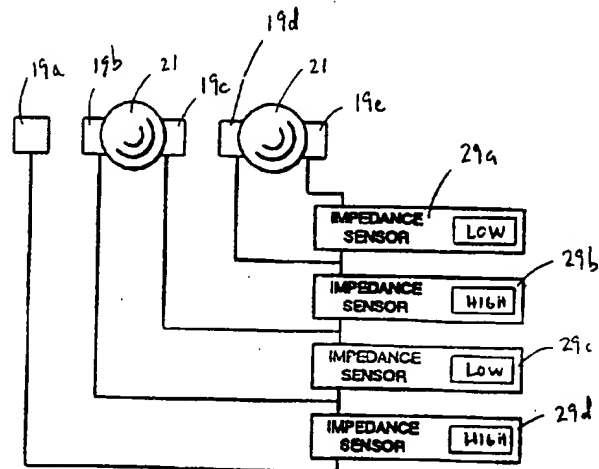


Fig. 3

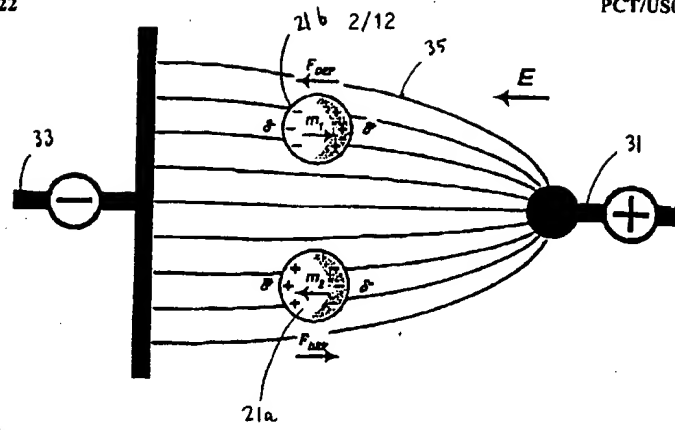


FIG. 2

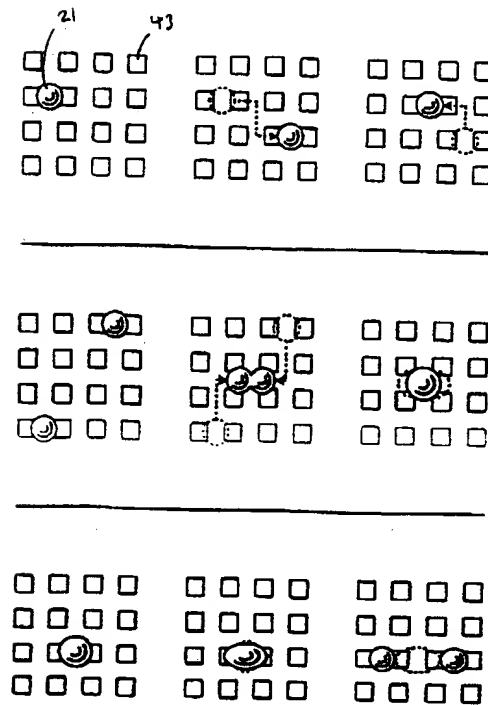


FIG. 12

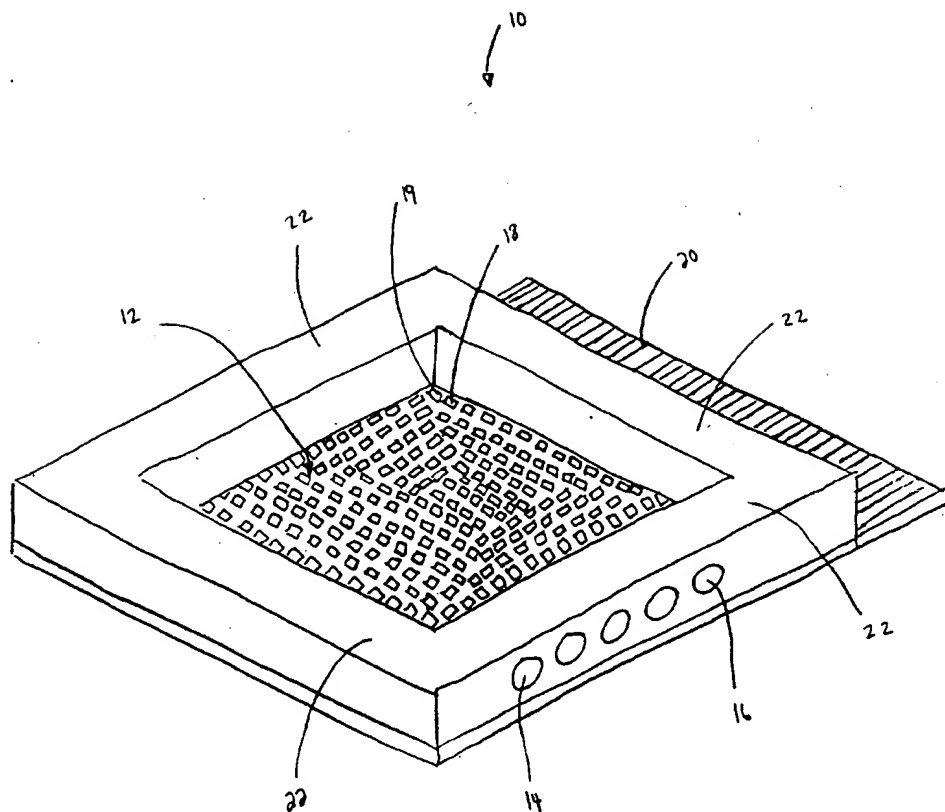


FIG. 4

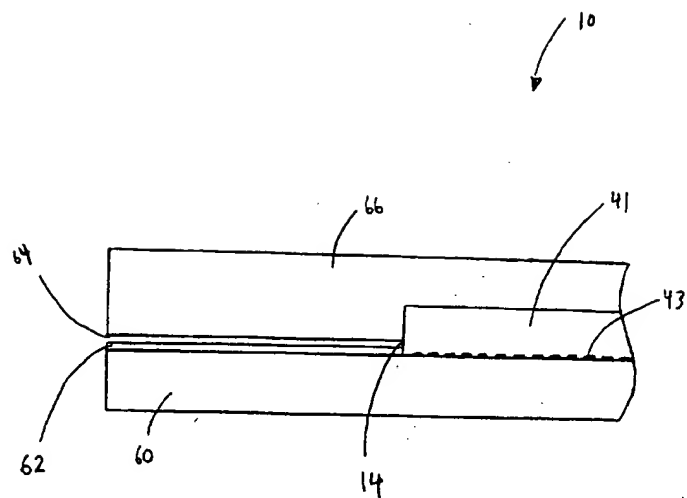


FIG. 5

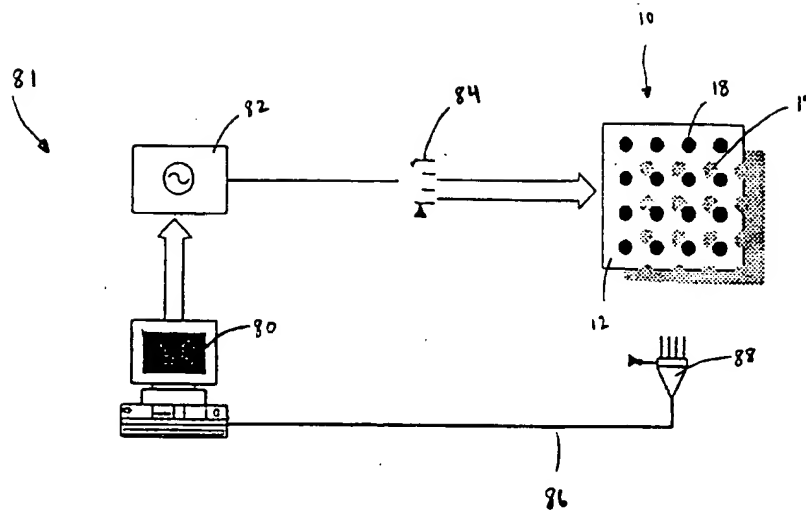


FIG. 6

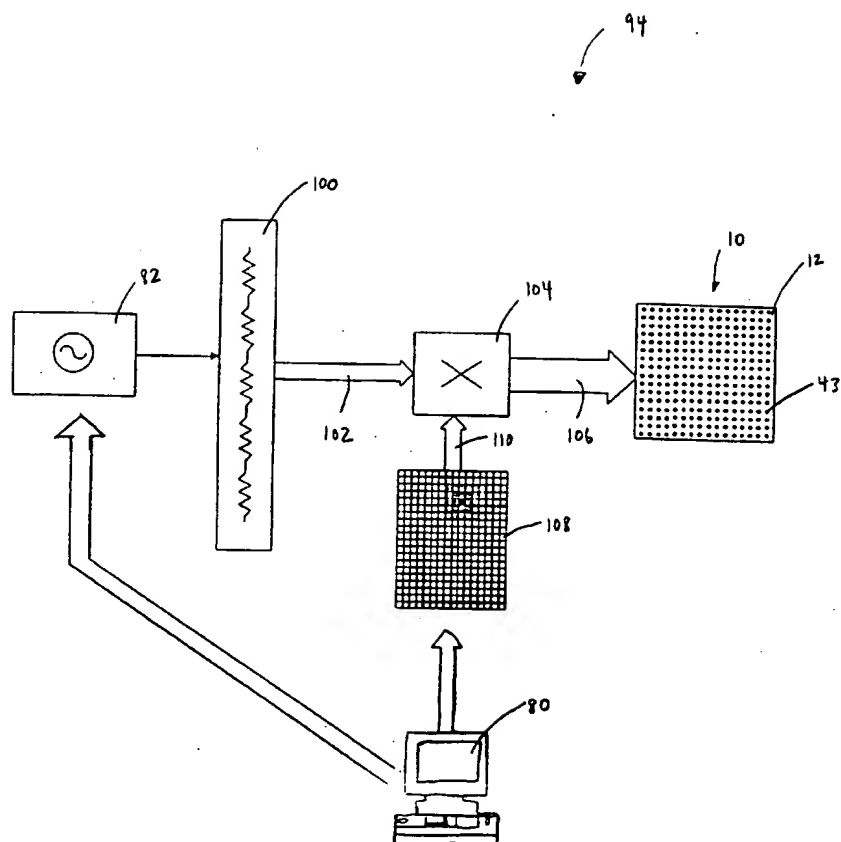


FIG. 7

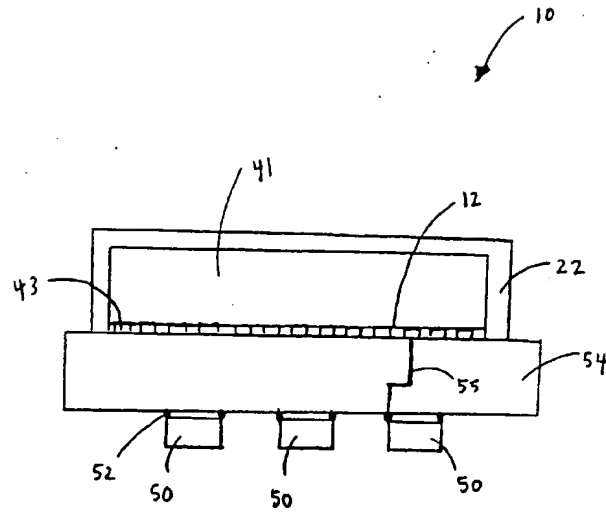


FIG. 8

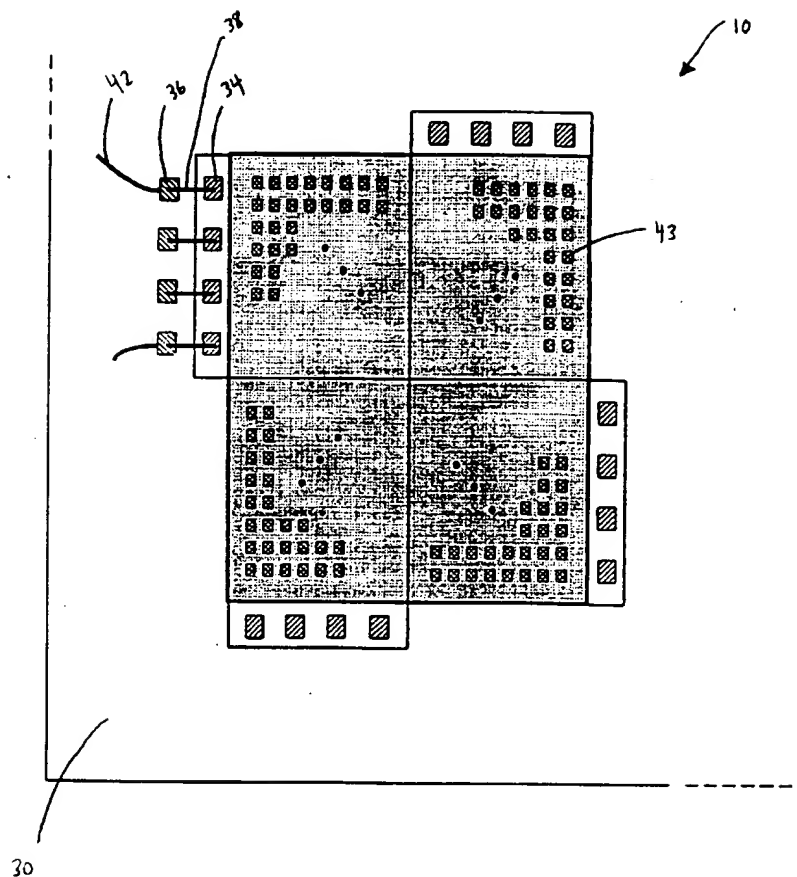


FIG. 9

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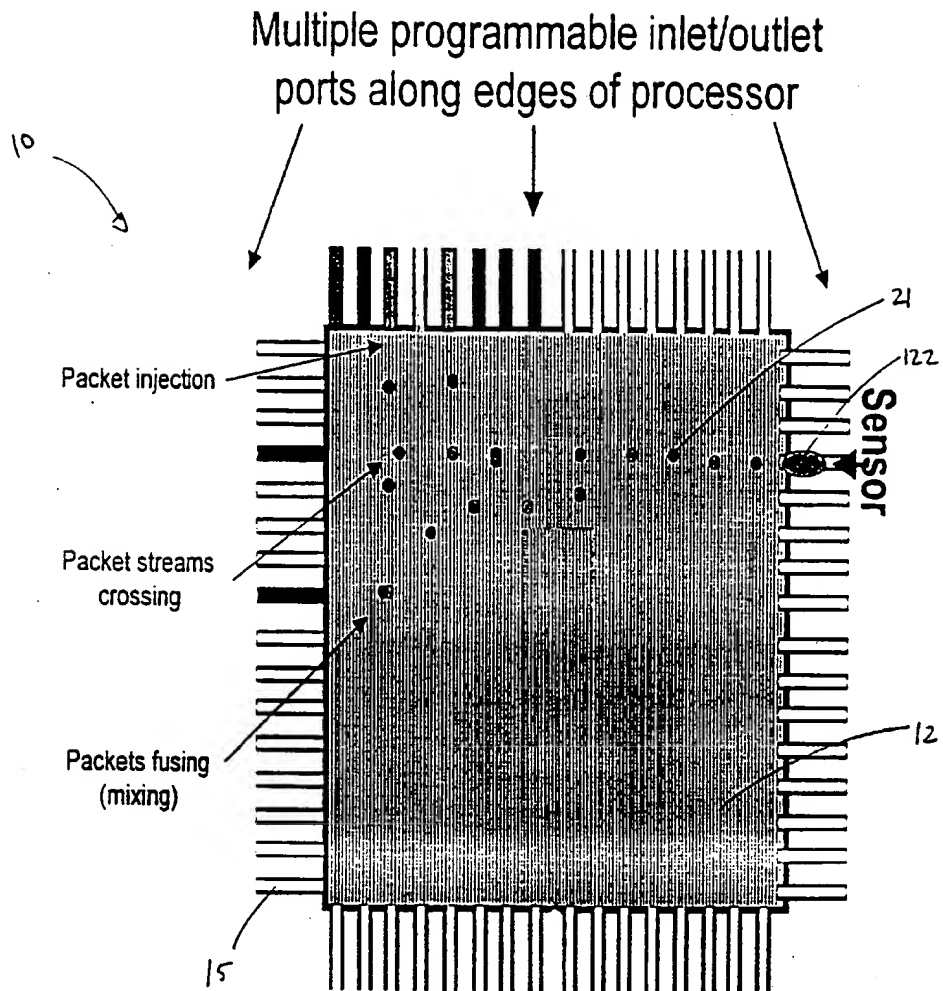


FIG. 9B

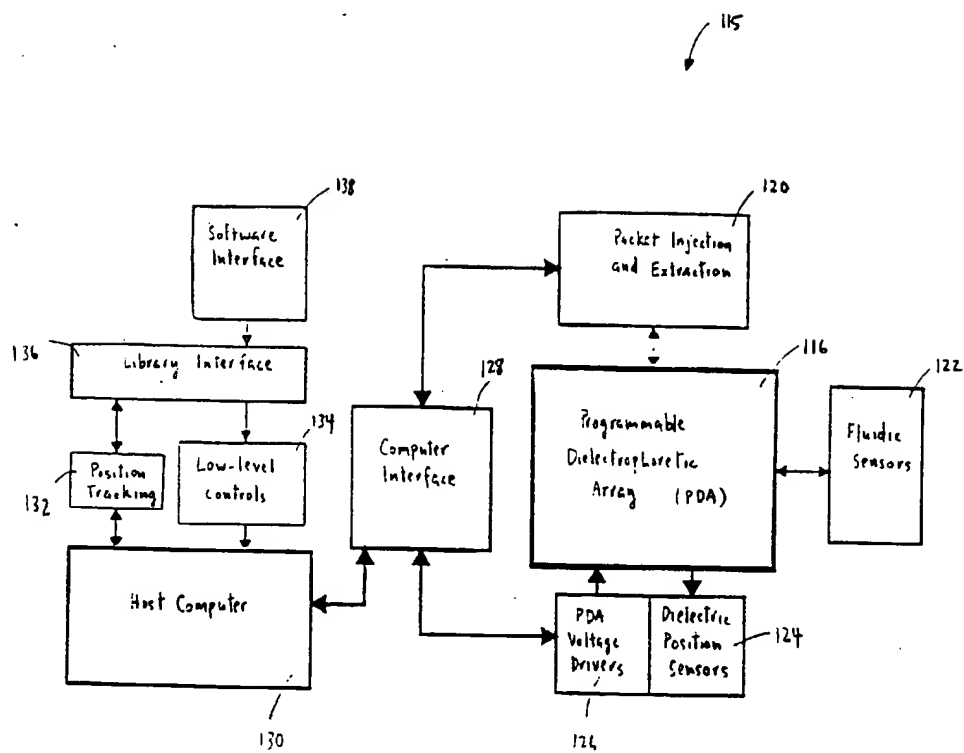


FIG. 10

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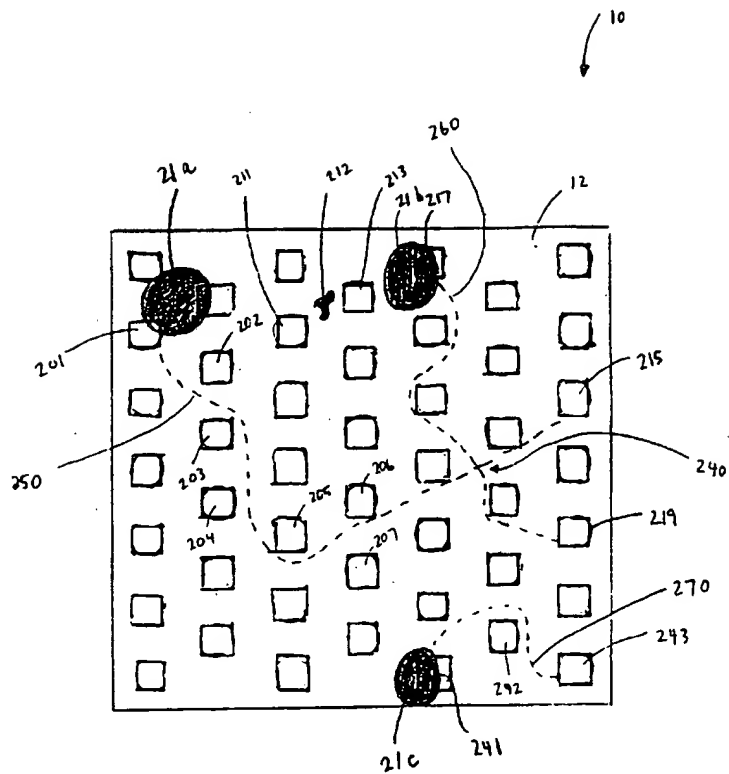


FIG. 11

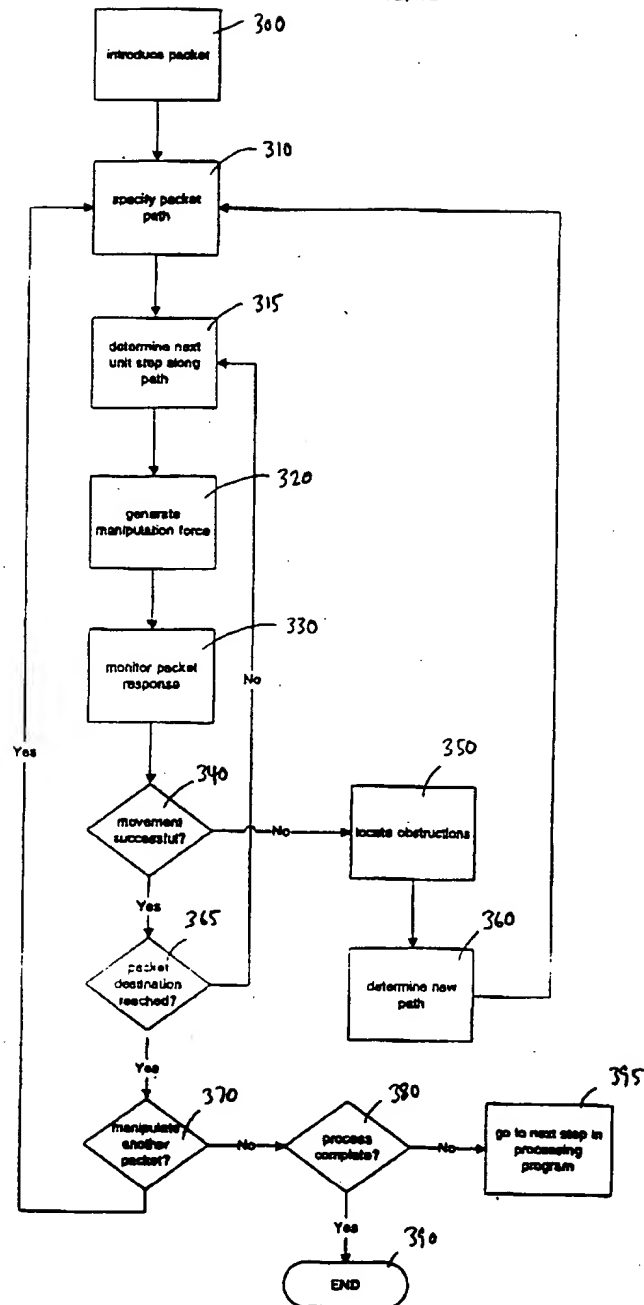


FIG. 13